FINAL PERFORMANCE REVIEW

SATELLITE POWER SYSTEM (SPS) MAGNETRON TUBE ASSESSMENT STUDY

CONTRACT NAS8-33157

(NASA-CR-161547) SATELLITE POWER SYSTEM (SPS) MAGNETRON TUBE ASSESSMENT STUDY Final Performance Review (Raytheon Co.) 99 p HC A05/MF A01 CSCL 10A
N80-30897
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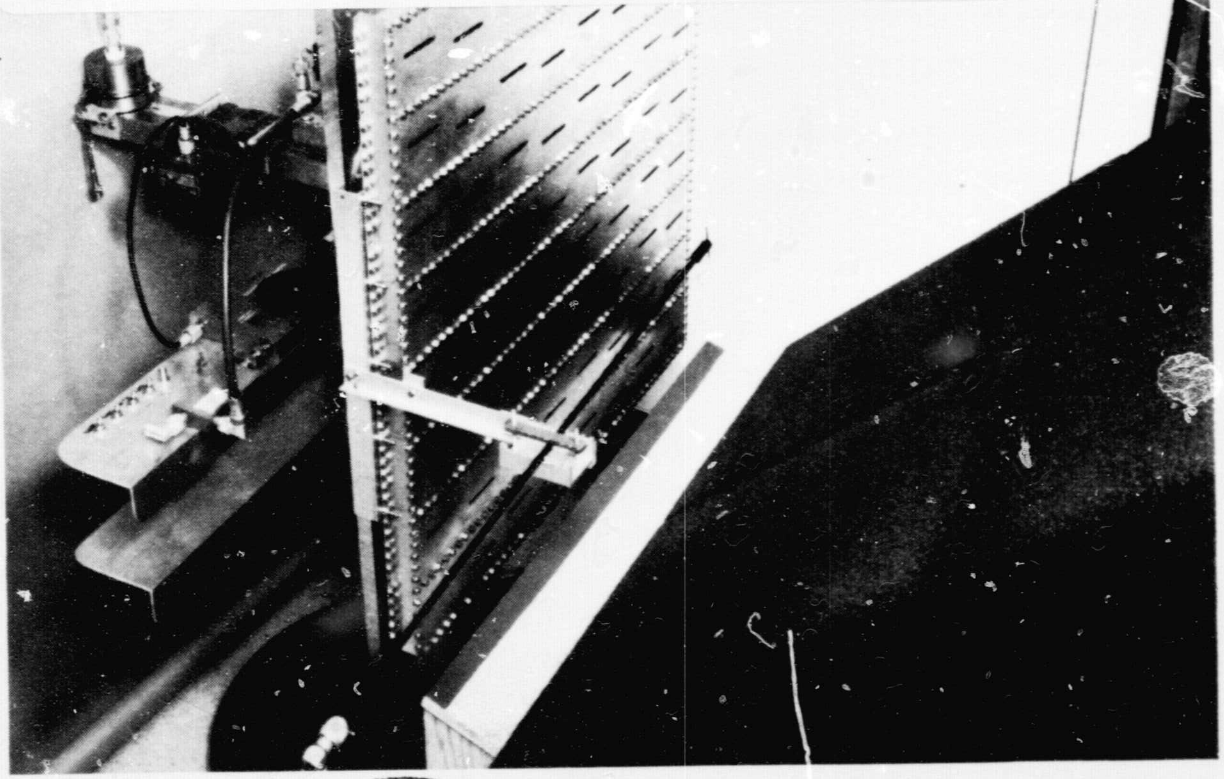

AUGUST 12, 1980

RAYTHEON

ERRATA SHEET

"Projected Characteristics of Magnetron Package"

Item 14 should read -114 dB/kHz.

Many items in "Comment Column" refer to sections of the final report rather than to the performance review.

"Radiated Noise and CCIR Requirements"

The table itself is believed to be correct but certain items on the facing page are inaccurate.

In the 5th line of the third paragraph on the facing page, 26 dB should be 24 dB, and 32 dB should be 45 dB.

In the 8th line of the third paragraph on the facing page, 32 dB should be 45 dB.

Final Performance Review*

SATELLITE POWER SYSTEM (SPS) MAGNETRON TUBE ASSESSMENT STUDY

Contract NAS8-33157

Prepared for

George C. Marshall Space Flight Center
National Aeronautics and Space
Administration
Huntsville, Alabama

By

Raytheon Company
Microwave and Power Tube Division
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August 12, 1980

*MA03

STUDY OBJECTIVES

The objective of this study is to provide MSFC and NASA with additional accurate and sufficient data and information to allow the SPS system study activities to evaluate the potential role of magnetrons in the SPS concept and make recommendations to management.

In carrying out the two major tasks the contractor shall make maximum use of past SPS studies and other associated data as appropriate. This is particularly the case for Task 2.0 where much information exists in the literature and from other contracts. In particular the following NASA contracts supply useful inputs.

LeRC Contract NAS 3-17835	Microwave Power Transmission System Studies NASA CR-134886
LeRC Contract NAS 3-20374	Design, Fabrication and Testing of a Crossed Field Amplifier for Use in the Solar Power Satellite NASA CR-159410
JPL Contract 955104	Microwave Beamed Power Technology Raytheon PT-5613

In addition, information obtained from a recent Raytheon Independent Research program on the role of the circuitry associated with the mechanical support of the cathode is of importance.

STUDY OBJECTIVES

PRODUCT

- REPORTS DESCRIBING THE ITEMS ADDED TO THE LABORATORY DATA BASE FOR THE MAGNETRON DIRECTIONAL AMPLIFIER
- DEFINE A TECHNOLOGY DEVELOPMENT PROGRAM TO DEVELOP THE MAGNETRON DIRECTIONAL AMPLIFIER FOR SPS USE

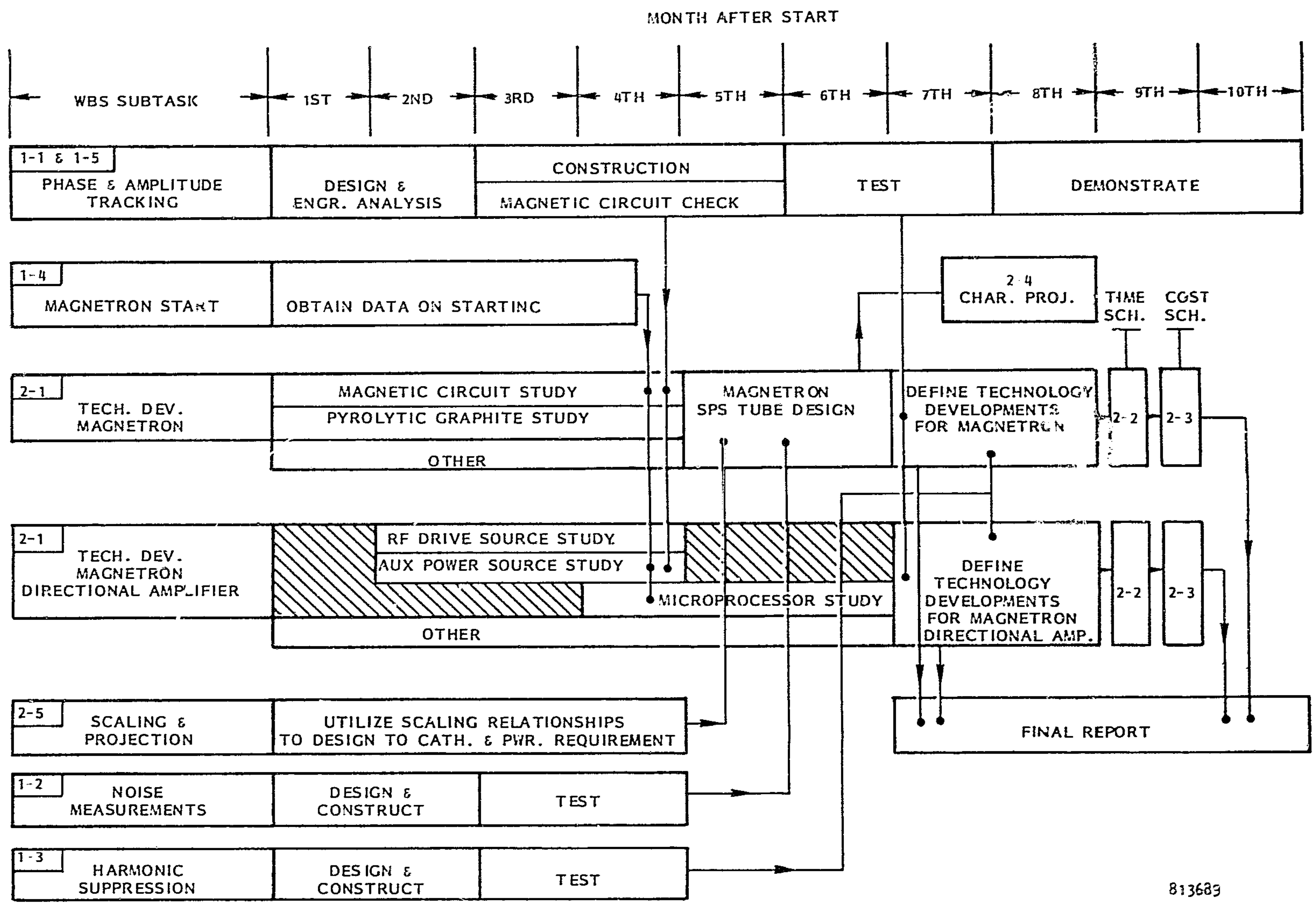
TASKS

- EXTENSION OF THE LABORATORY DATA BASE ON THE MAGNETRON DIRECTIONAL AMPLIFIER
- PROJECTION OF THE MAGNETRON DIRECTIONAL AMPLIFIER TECHNOLOGY

ACTIVITY FLOW CHART

The activity flow chart on the facing page breaks down the study into its various components and indicates the relationship among them.

The major effort in the study was to obtain additional data to expand the data base. Most of that effort was to have occupied the early part of the study, leaving the definition of the technology development program as the final portion of the effort. This document reports upon the overall effort.



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Activity Flow Chart

MATERIAL TO BE REVIEWED

The achievements to be reviewed are broken down by subject on the facing page. The first four are considered to be of the most general interest. The next three items are back up studies to support the design of the magnetron directional amplifier for the SPS.

The subject of noise measurements is of general interest in that it introduces an improved sensitivity of 30 to 40 dB in making such measurements.

Athough no final details of the tube design for the SPS have yet been determined, the initial scaling is of interest in that it has been possible to establish the approximate mass of the tube. This was then combined with an estimate of the mass of the slotted waveguide array and the associated microwave plumbing to arrive at an estimate for the overall mass of the transmitting antenna without supporting structure.

SUMMARY OF ACHIEVEMENTS

TO BE REVIEWED

- DEMONSTRATION OF TRACKING OF PHASE AND AMPLITUDE OF THE MICROWAVE OUTPUT TO PHASE AND AMPLITUDE REFERENCES
- CONCEPT TO GREATLY EXPAND RANGE OF POWER OVER WHICH MAGNETRON DIRECTIONAL AMPLIFIER WILL OPERATE
- REALIZATION THAT AMPLITUDE CONTROL IS IMPORTANT IN OVER-ALL SYSTEM DESIGN AND IN SIMPLIFYING POWER CONDITIONING
- A PRELIMINARY DESIGN FOR THE OVERALL ARCHITECTURE OF THE POWER MODULE
- DEMONSTRATION OF MAGNETRON STARTING USING THE AMPLITUDE CONTROL SYSTEM
- MATHEMATICAL MODEL AND COMPUTERIZED STUDY OF THE PYROLYTIC GRAPHITE RADIATING FIN
- MAGNETIC CIRCUIT STUDY DEFINING THE MASS OF THE MAGNETIC CIRCUIT FOR THE SPS TUBE
- NOISE MEASUREMENTS WITH GREATLY INCREASED SENSITIVITY TECHNIQUES
- HARMONIC SUPPRESSION BY NOTCH REFLECTION FILTERS
- ESTIMATE OF THE MASS OF THE TRANSMITTING ANTENNA BASED UPON TUBE AND SLOTTED WAVEGUIDE ARRAY MASS ESTIMATES
- STUDY OF AUXILIARY SOURCES OF POWER
- DEVELOPMENT OF MAGNETRON PACKAGE WITH POWER GENERATION, PHASE CONTROL AND POWER CONDITION FUNCTIONS
- PROJECTION OF MAGNETRON PACKAGE CHARACTERISTICS
- DEFINITION OF A TECHNOLOGY DEVELOPMENT PROGRAM TO DEVELOP THE MAGNETRON DIRECTIONAL AMPLIFIER FOR SPS USE

PHASE AND AMPLITUDE TRACKING

Phase and amplitude tracking is of universal importance in the SPS transmitting antenna. Because there had never been any experience with designing a phase and amplitude tracking capability into the magnetron directional amplifier there was understandable skepticism about being able to do so.

The most effective manner to remove such skepticism seemed to be to build a test bed and to demonstrate phase and amplitude tracking. The more components that could be incorporated into the test bed the better.

Although the control loops used in the phase and amplitude tracking demonstration test bed are comparatively simple in the hierarchy of control theory, they are essentially adequate for the task.

PHASE AND AMPLITUDE TRACKING

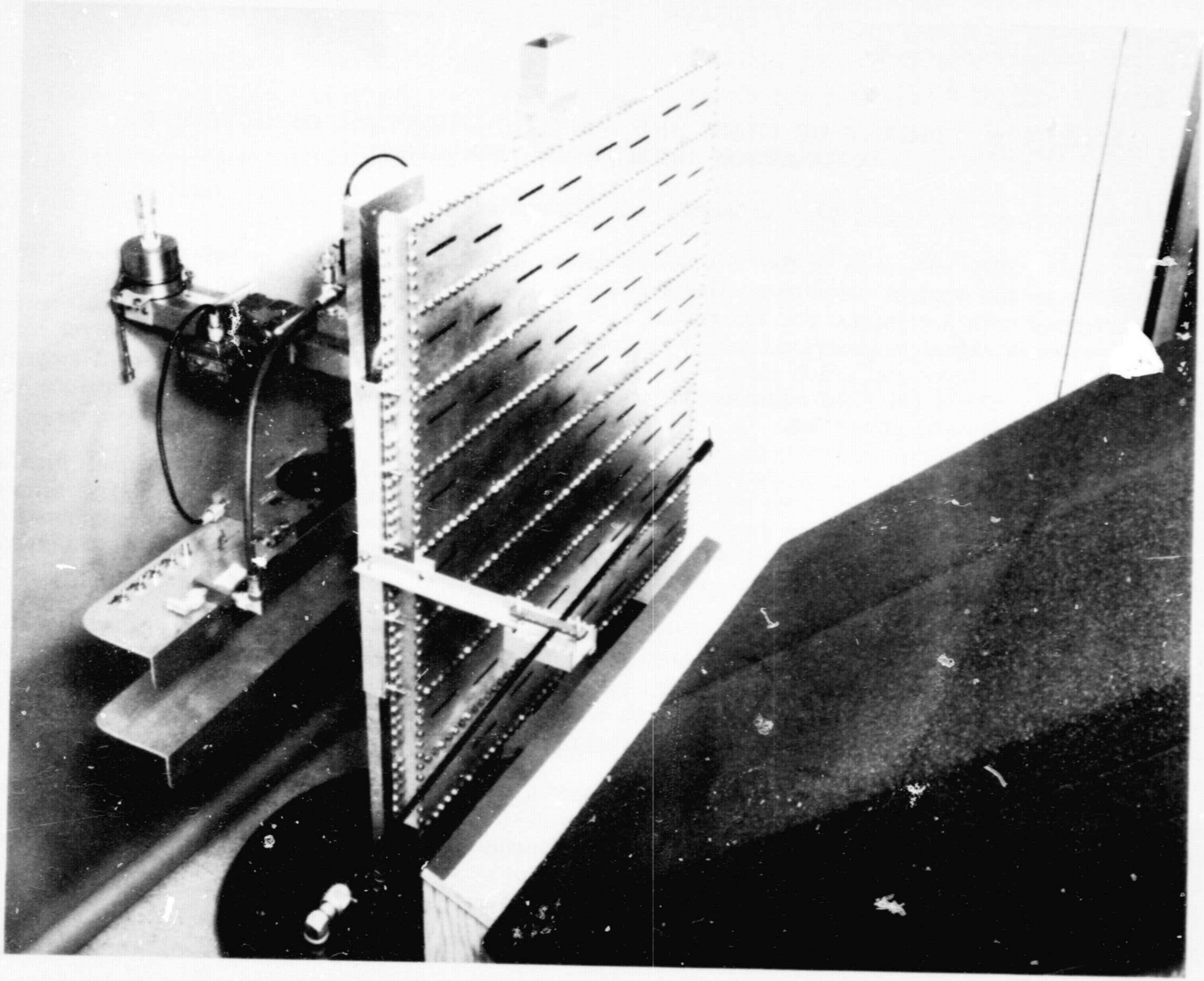
- A UNIVERSAL REQUIREMENT IN THE SPS
- TIGHT PHASE TRACKING NECESSARY FOR ANTENNA EFFICIENCY
- AMPLITUDE TRACKING TO A REFERENCE DESIRABLE FOR OVERALL SYSTEM OPERATION AND ALSO FOR ANTENNA EFFICIENCY
- DEMONSTRATION GIVEN TO MICROWAVE SUBSYSTEM INTEGRATOR, ROCKWELL INTERNATIONAL
- DEMONSTRATION CONSISTED OF PACKAGE CONTAINING MAGNETRON DIRECTIONAL AMPLIFIER, SLOTTED WAVEGUIDE RADIATING ANTENNA, AND FEEDBACK CONTROL LOOPS FOR PHASE AND AMPLITUDE TRACKING
- THEORETICAL ANALYSIS OF CONTROL LOOP FOR AMPLITUDE CONTROL WAS PERFORMED
- CONSIDERATION WAS GIVEN TO THE PHYSICAL LOCATION OF THE SOLID STATE DEVICES THAT MUST BE USED IN THE CONTROL CIRCUITS
- CONCEPT TO EXPAND OPERATING RANGE OF MAGNETRON DIRECTIONAL AMPLIFIER WAS INVESTIGATED AND INCORPORATED INTO MAGNETRON PACKAGE DESIGN

TYPICAL PHASE AND AMPLITUDE TRACKING DATA

The graph on the facing page demonstrates the excellence of the amplitude tracking data. The "blackest" contours are obtained by setting the reference power level to a value which will remain constant while the voltage of the voltage-regulated power supply is changed from a value of about 3300 volts to 4900 volts or a ratio of 1.48. There is a power level associated with each of the points on the curve and the values at two ends of the curve indicate the power extremes. One example is 716 watts at the top end and 687 at the bottom, giving a ratio of 1.042. Thus, the power output is held to the power reference within $\pm 2\%$. This is a value predicted by theory.

The phase contours shown are readings taken from the coaxial phase shifter and are equal and opposite to the phase shift taking place in the tube as a function of applied voltage and current. This equivalence is made possible because the output error voltage of the phase comparator remains below the equivalent of a one degree tracking error over the entire performance chart. It is noted that the contours of phase shift through the tube follow very closely the contours of constant frequency if the same tube were operated as a free running oscillator.

The drive power level for this data was 10 watts. The range of voltage and current over which the tube can be operated is determined by this drive level, as subsequent data indicates.



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Photograph of Test Bed for Phase and Amplitude Tracking Demonstration.

SCHEMATIC DIAGRAM OF PHASE AND AMPLITUDE CONTROL OF OUTPUT OF MAGNETRON DIRECTIONAL AMPLIFIER

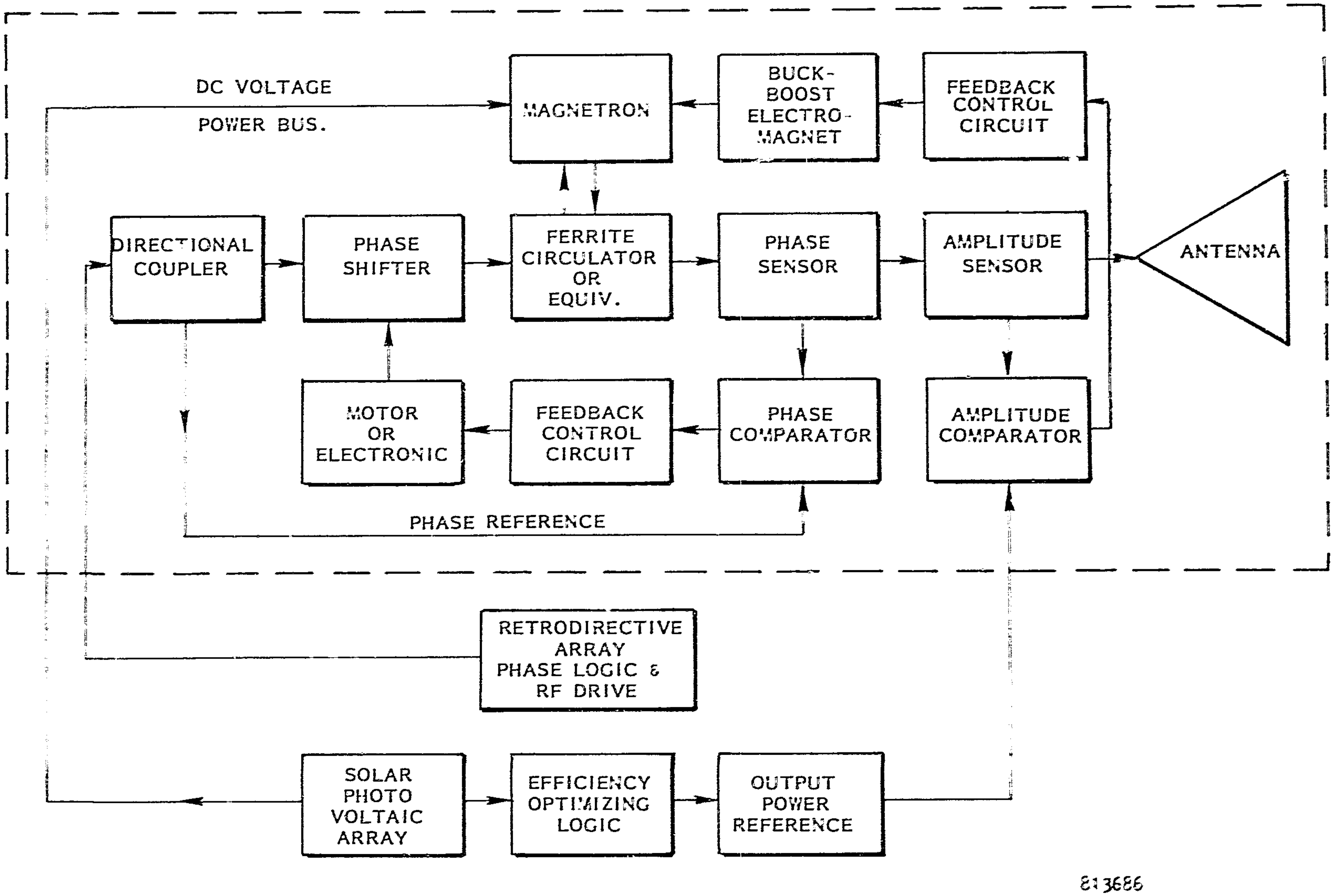
The diagram on the facing page is largely self explanatory.

The output power reference in the test bed is simply a voltage in the one to two volts range that is introduced into the control circuitry. The amplitude of the output of the magnetron directional amplifier is sensed with a crystal. The DC output voltage of the crystal is compared with the reference voltage and an error signal is generated which activates the feedback control loop. The control loop makes use of the buck boost coil which either adds to or subtracts from the field of the permanent magnet on the magnetron. The total field controls the operating voltage of the magnetron and therefore its response to the DC voltage power bus.

The output phase reference is obtained in the test bed by sensing the incoming signal with a directional coupler. This reference phase signal is then compared with that coming from the phase sensor at the amplifier output, and the error signal used to operate a mechanical phase shifter to compensate for any phase shift in the tube caused by a shift in input current or voltage, or a number of other factors such as temperature change and operating life.

In the test bed a mechanical phase shifter was used for two reasons. First, it was by far the simplest and most economical. Secondly, it was planned to operate the tube over a broad range of microwave drive levels, including 50 watts, which would have been a very difficult requirement for any other form of phase shifter. An unexpected benefit was the use of the calibration of the phase shifter to determine the phase shift through the magnetron directional amplifier.

An expected technology development requirement would be a suitable phase shifter that would respond rapidly and without mechanical friction. Such an arrangement in the form of a solenoid actuated tuner supported on a compliant membrane in the magnetron package has been proposed. In this arrangement the phase shifter would be eliminated and the output of the feedback control circuit fed to the solenoid or "voice coil" positioned in the magnetron.



Schematic Diagram of Phase and Amplitude Control ⌐ Output of Magnetron Directional Amplifier. The Proposed Packaged Unit is Enclosed in Dotted ..ie. Relationship to SPS Overall System is Indicated Outside of Dotted Line.

TYPICAL PHASE AND AMPLITUDE TRACKING DATA

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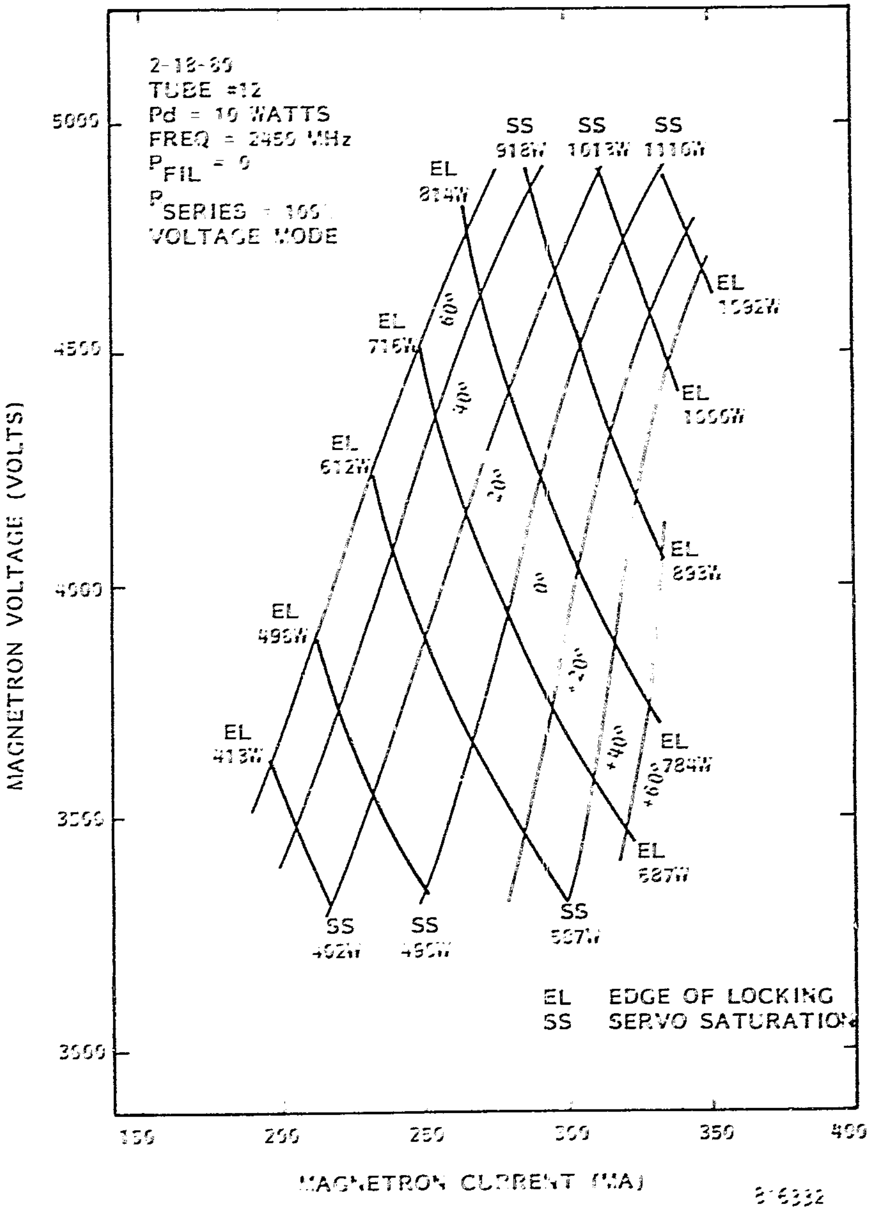


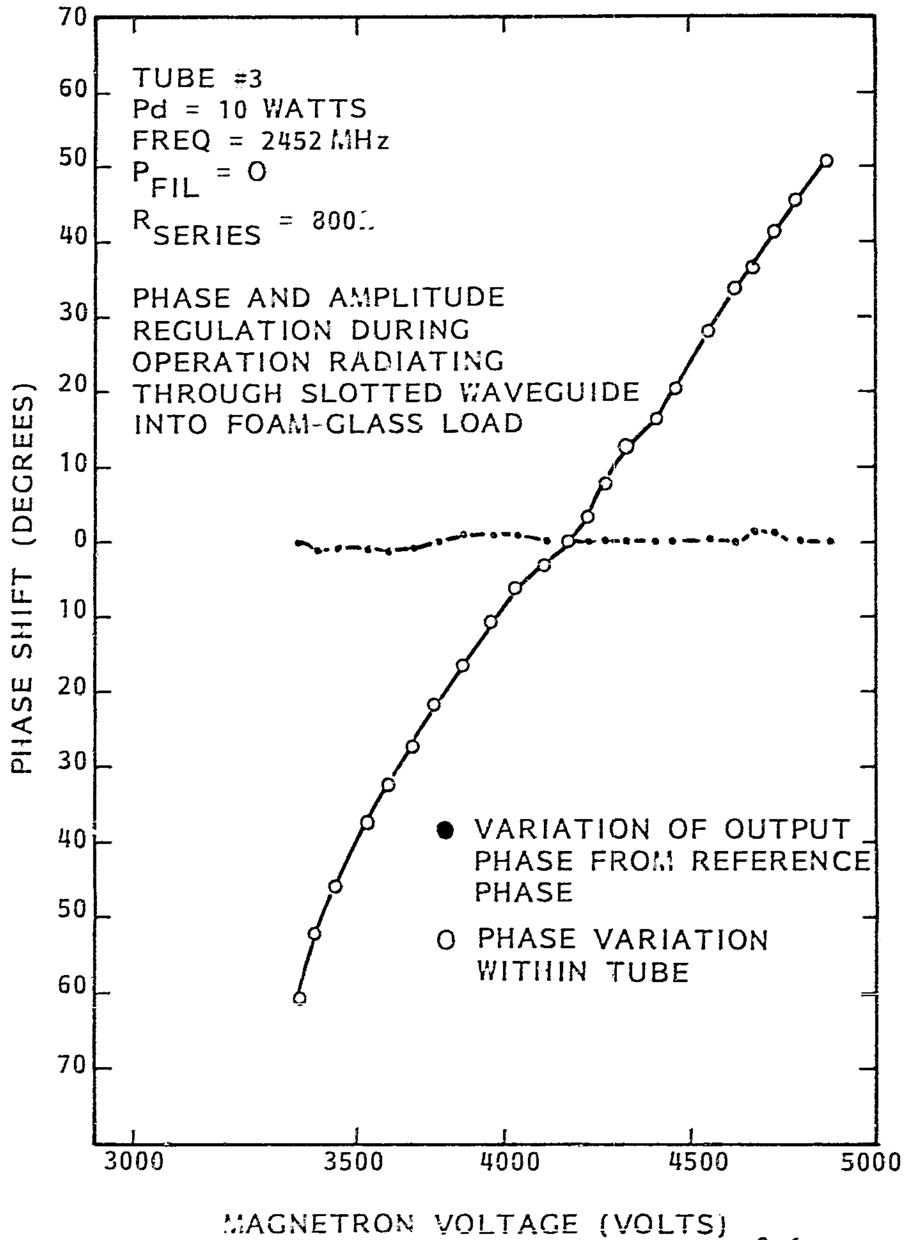
Phase and Amplitude Tracking Data with Series Resistance Reduced to 100 ohms to Simulate Operation Across a Hard Voltage Bus.

TRACKING OF OUTPUT PHASE TO REFERENCE

An excellent method to illustrate how well the output phase of the magnetron directional amplifier follows a reference phase is to place a pickup probe in front of the slotted waveguide radiator which is the load for the directional amplifier, and then to feed the output of the probe into a Hewlett Packard network analyzer to compare the monitored phase with the phase reference.

The results of this method are shown in the graph on the facing page. These data show that the output phase is controlled to within ± 1 degree over an operating voltage range of 3500 to 4800 volts while the amplitude of the output is being held constant to within $\pm 3\%$ over this same range. Over the range the actual phase shift occuring within the magnetron directional amplifier is ± 60 degrees as shown in the data. The internal phase shift is cancelled out by the phase shift provided by a phase shifter at the input to the tube which is controlled by the negative feedback control system.

PHASE PERFORMANCE



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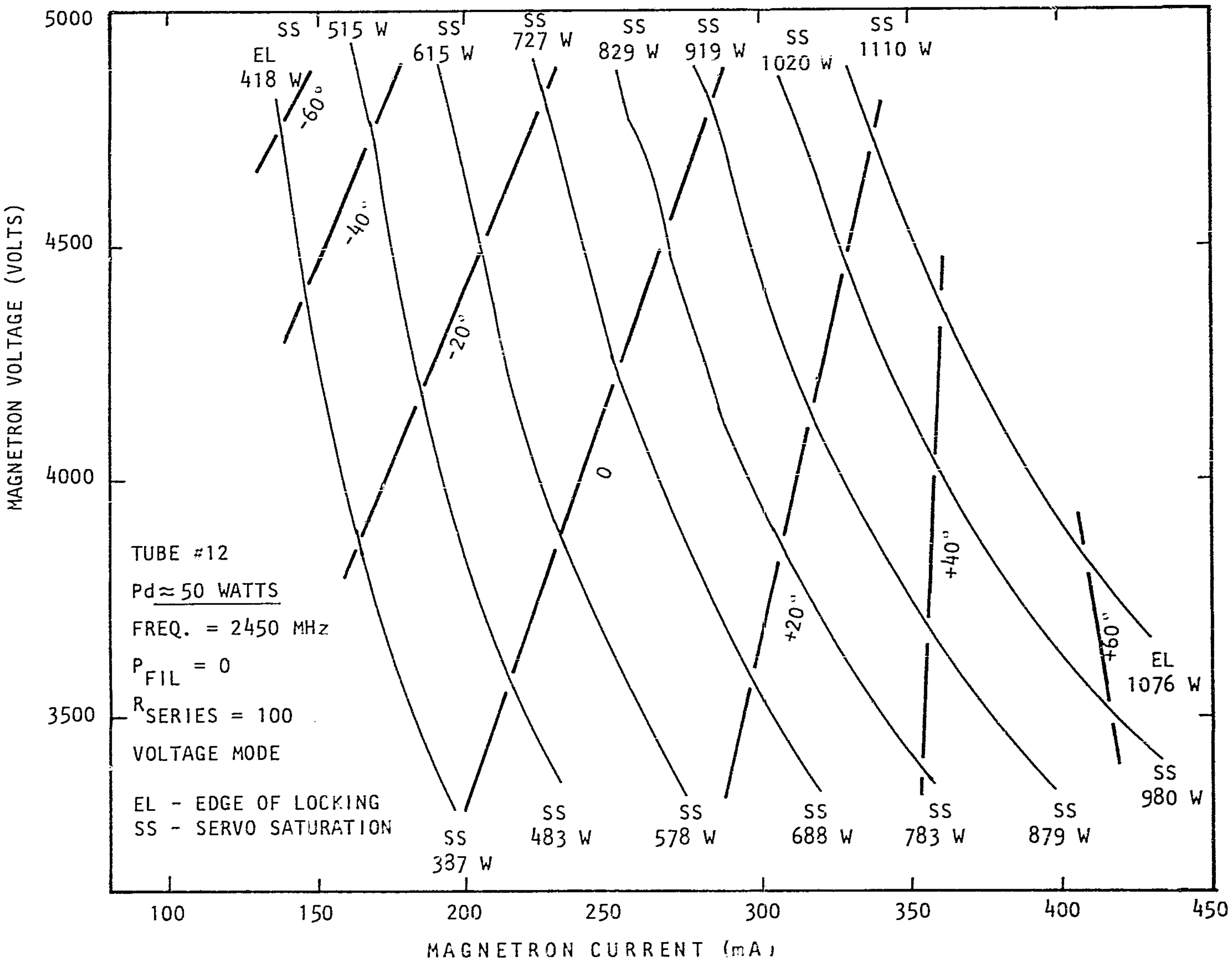
INCREASED OPERATING RANGE WITH INCREASE DRIVE

The locking range is roughly proportional to the square root of the drive power. Thus, at a 50 watt drive level the range of current over which operation can be maintained is more than twice as great as with the 10 watt drive level.

PHASE AND AMPLITUDE TRACKING

50 WATT DRIVE LEVEL



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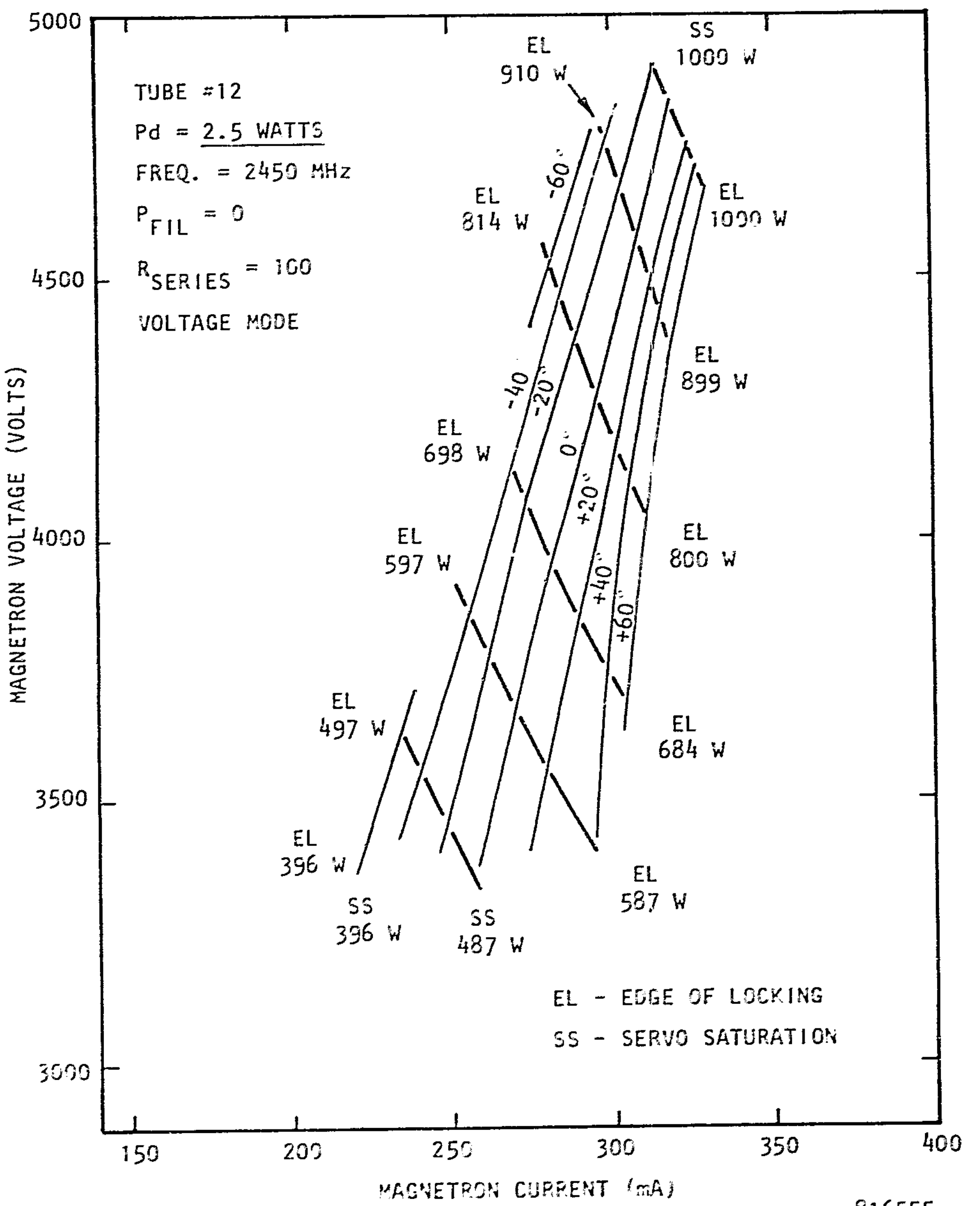
DECREASED OPERATING RANGE WITH DECREASED DRIVE

A reduction of the drive level from 10 watts to 2.5 watts reduces the operating range by a factor of approximately two.

Retuning the magnetron as explained on the next page will permit a range of operation much larger than that shown for the same drive level.

PHASE AND AMPLITUDE TRACKING

2.5 WATT DRIVE LEVEL



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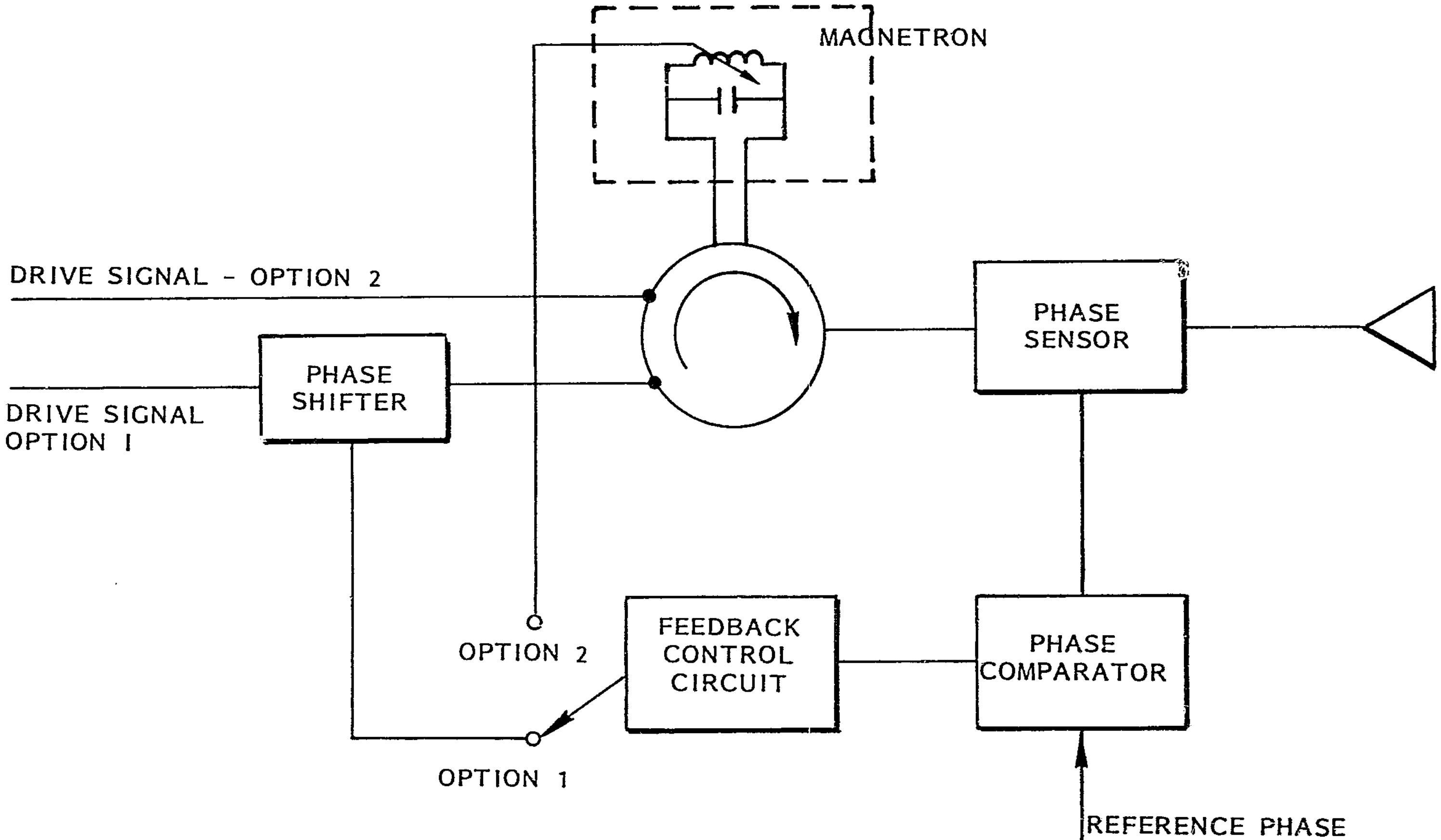
MAGNETRON TUNING TO INCREASE THE OPERATING RANGE OF THE MAGNETRON DIRECTIONAL AMPLIFIER

One of the limitations placed on the use of the magnetron directional amplifier is that a requirement to operate over a large range of anode current and voltage requires substantial drive power and a consequent reduction in gain.

This limitation can be removed by using the existing phase control loop to retune the magnetron so that its free running frequency is equal to that of the drive signal. A tuning range of as small as 1% that can be easily achieved with an internal tuner would make the complete operating range of the tube accessible at large values of gain. The tuner can be applied to the magnetron design as shown in a subsequent section by supporting it on a compliant member and driving its motion by a solenoid, or "voice coil". Thus there is no movement involving mechanical sliding friction and the response time will be within a few milliseconds. Further, the tuning of a magnetron by a mechanically moveable element is a standard practice for tuning ranges much greater (10% typically) and therefore much more difficult to achieve than the 1% proposed for this application.

There is even one magnetron, the 6177 that has a 2% tuning range with the "voice coil" driver contained within the vacuum envelope. This tube is routinely used for microwave altimeter applications.

The schematic on the opposite page shows how the same control circuit can be used for phase tracking by either external phase shifter or by magnetron tuning.



OPTION 1 IS CONVENTIONAL APPROACH ALREADY EXPERIMENTALLY DEMONSTRATED

OPTION 2 IS IMPROVED CONCEPT UTILIZING "VOICE COIL" INDUCTIVE TUNING OF MAGNETRON

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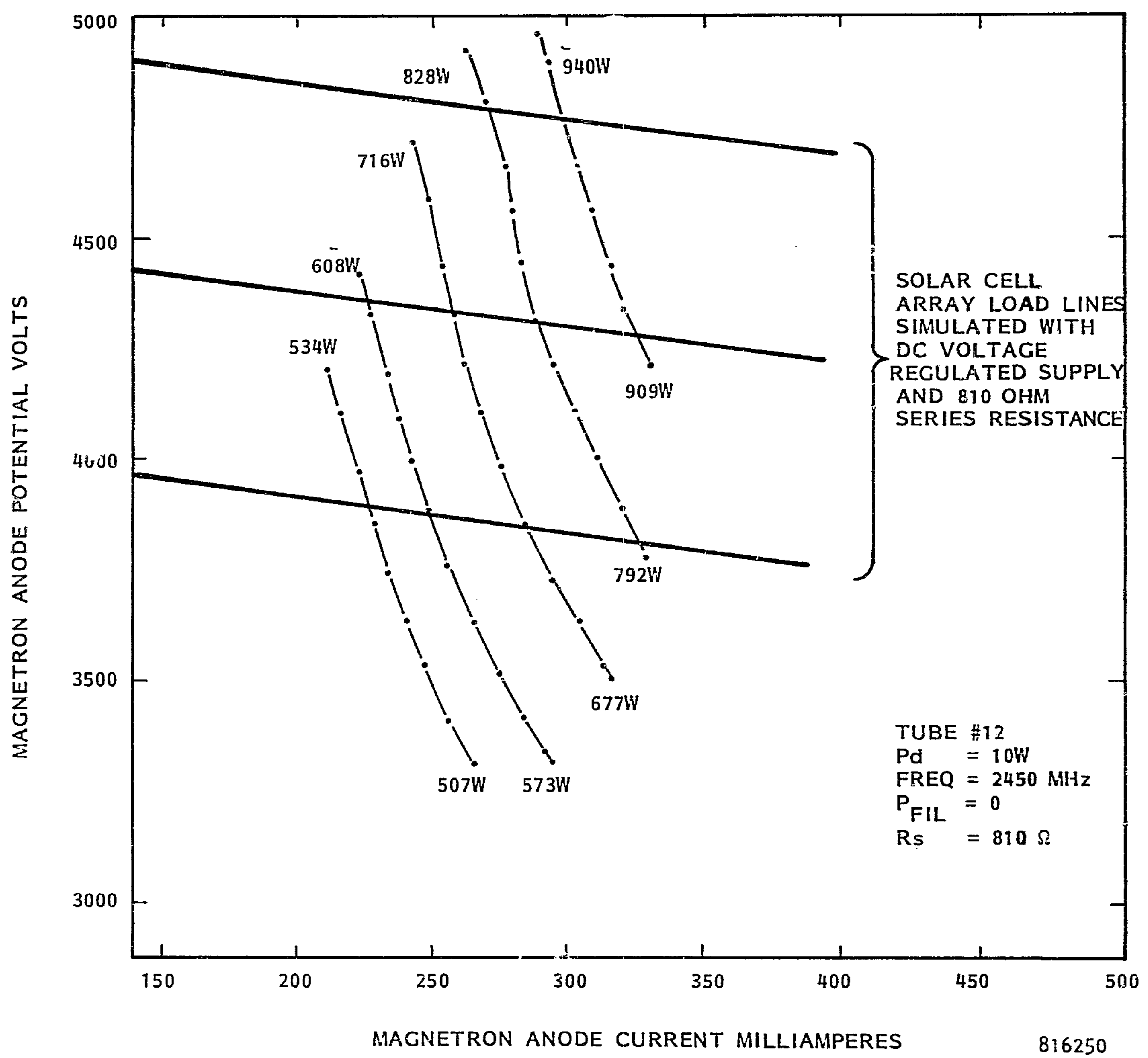
A Comparison of Present Phase Control Arrangement with Proposed Magnetron Tuning Which Provides Fast, Frictionless, Response and Broad Operating Range.

SIMULATION OF INTERACTION WITH SOLAR CELL ARRAY

To simulate the interaction of the whole bank of magnetron directional amplifiers with the solar cell array, the slope of the voltage-current characteristic of the solar cell array was simulated with an 810 ohm resistor in series with the voltage regulated power supply.

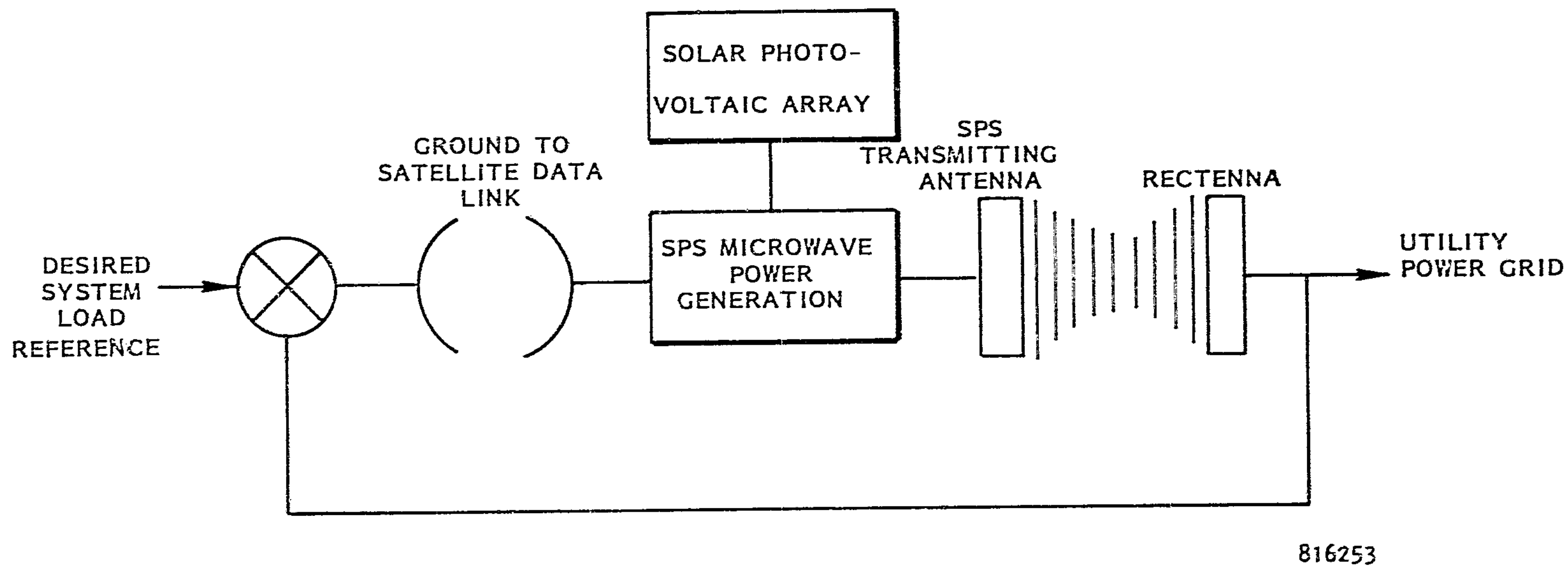
The graph on the facing page shows how the curves of constant power output as determined by the reference voltage intersect with the voltage current characteristics of the solar cell array which are determined by the open circuit voltage of the solar array and the internal resistance (810 ohms simulated in this case).



Experimental Data on the Amplitude Coı .ol System Shown in Which Interaction with the Solar Voltaic Array is Simulateu.

OVERALL CONTROL OF SPS SYSTEM UTILIZING AMPLITUDE CONTROL OF OUTPUT OF MAGNETRON

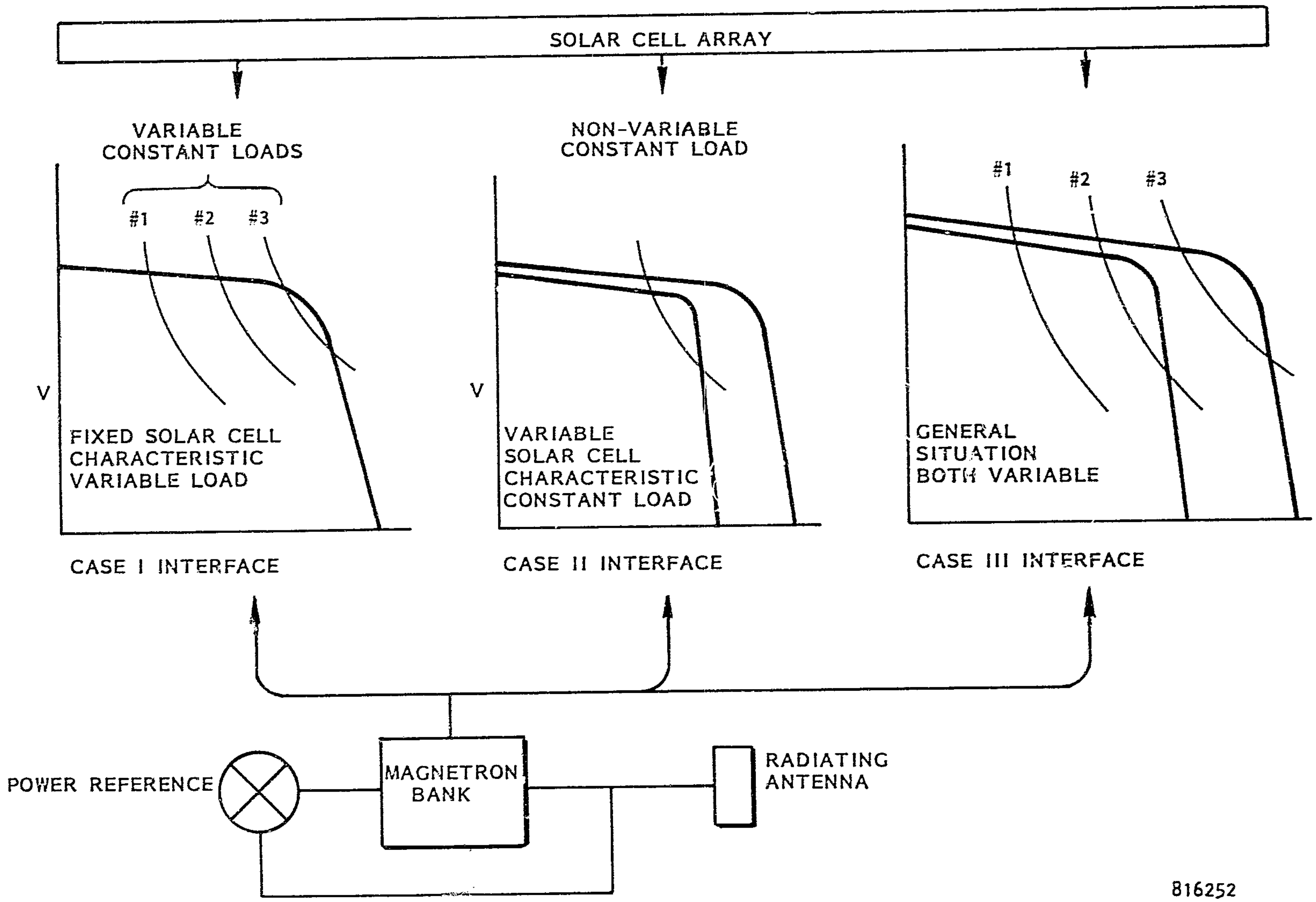
The facing page shows a simplified block diagram for the overall amplitude control system. The desired system load reference is the voltage level at which it is desired to operate the input to the power utility grid. The voltage level at the output of the rectenna is then sensed and compared with the reference level. Any voltage difference represents an error which is relayed to the satellite. This error is distributed throughout the satellite and added or subtracted to the reference power level (also in the form of a DC voltage) for each of the magnetrons. When the proper reference voltage is reached the microwave power reaching the ground is just sufficient to match the power requirements of the grid.



Overall Control System Showing How the Varying Demands of the Utility Power Grid can be Interfaced with the SPS Facility.

INTERFACE BETWEEN SOLAR CELL ARRAY AND BANK OF MAGNETRON DIRECTIONAL AMPLIFIERS

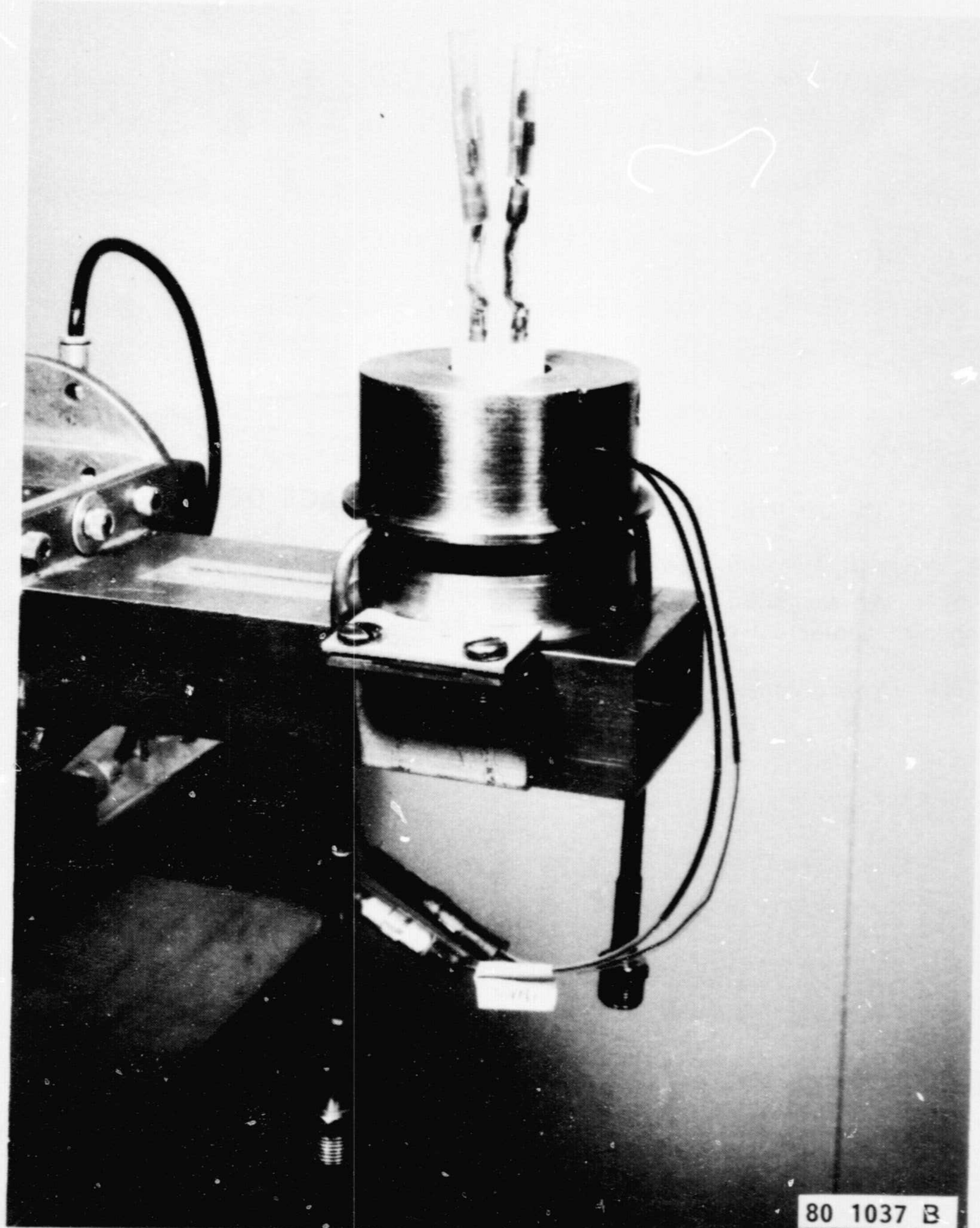
If the amplitude of the output of the microwave generator can be controlled remotely from a logic center, the power interface between the solar cell array and the microwave generator can be arbitrarily controlled.



Interface Between Solar Cell Array and Magnetron Directional Amplifier.

THE MAGNETRON REPACKAGED WITH A BUCK-BOOST COIL

The conventional microwave oven is stripped of its cooling fins and external hardware and repackaged with new permanent magnets, a buck-boost coil, and a magnetic return circuit.

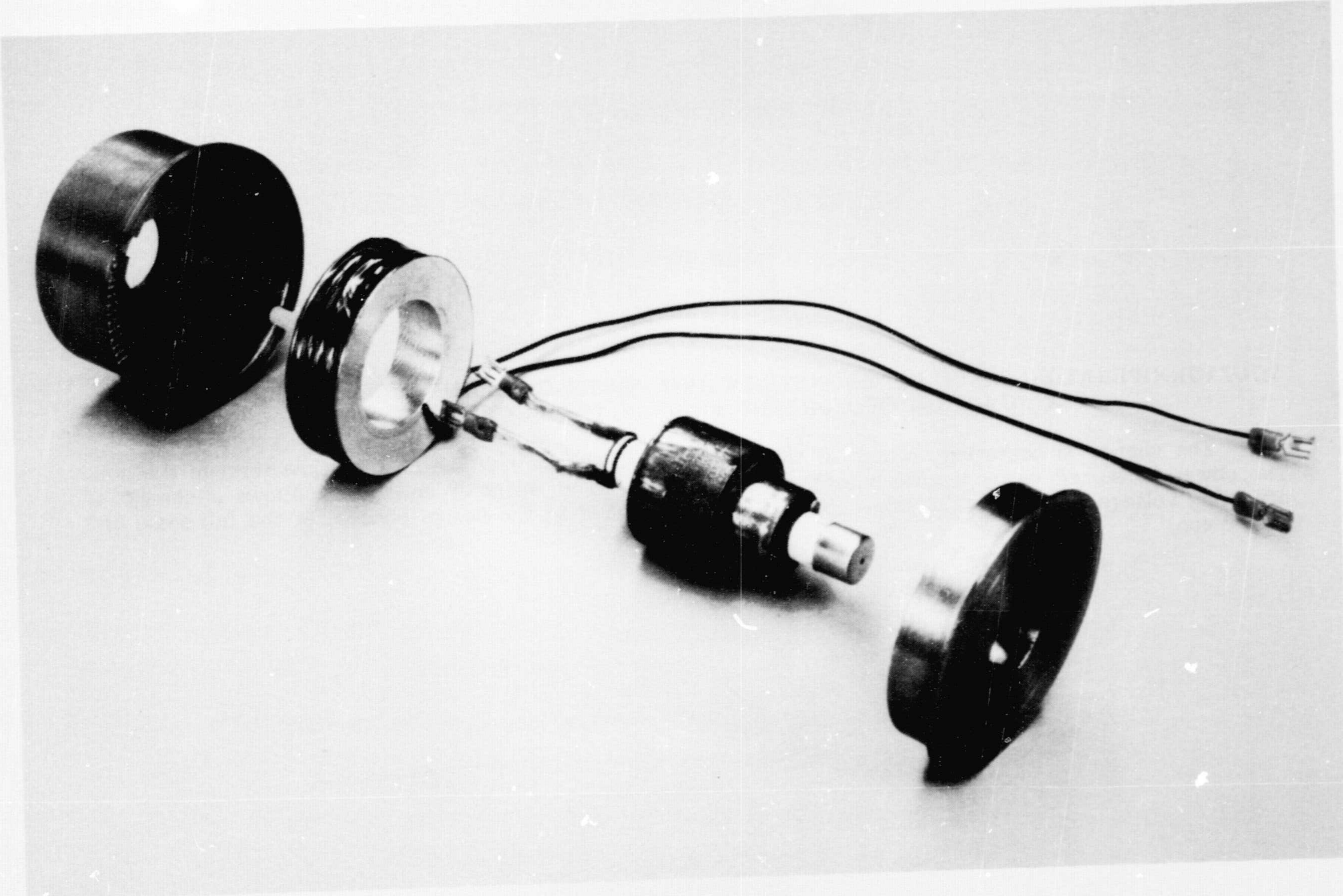


Photograph of the
Microwave Generator
and Buck Boost Coil
in an Integrated Package.

COMPONENTS MAKING UP THE PACKAGE OF MAGNETRON AND BUCK-BOOST COIL

An exploded view of the buck-boost coil and magnetron assembly is shown on the facing page. The special samarium-cobalt magnets are inside the top and bottom portions of the magnetic return circuit.

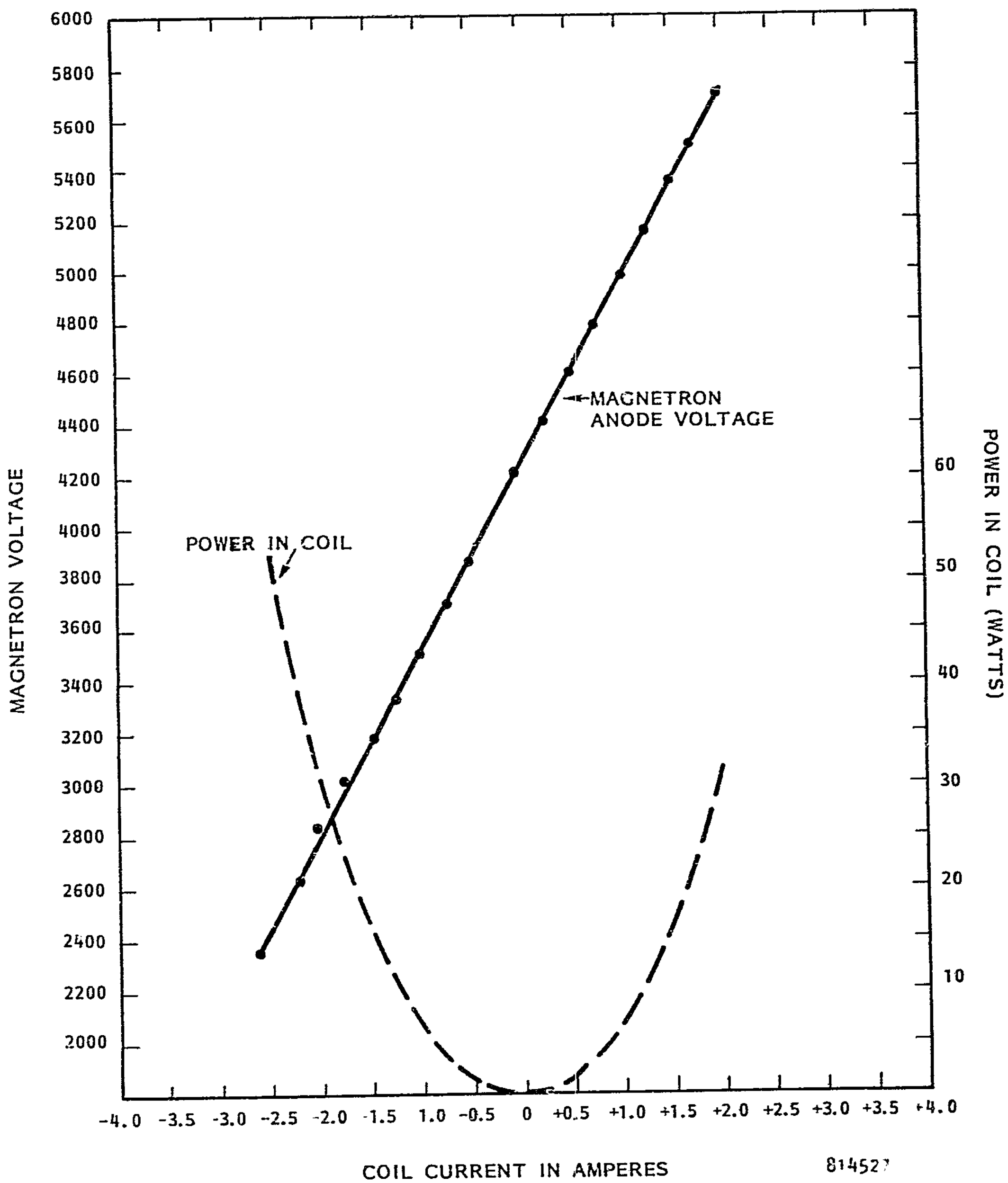
The complete assembly weighs about two pounds.



Modification of microwave oven magnetron showing (1) magnetron stripped of cooling fins and ceramic magnets (2) buck-boost coil (3) cold-rolled steel shell, and (4) samarium cobalt magnets (inside ends of each portion of shell).

VOLTAGE OPERATING LEVEL OF MAGNETRON AND POWER CONSUMED IN BUCK-BOOST COIL AS A FUNCTION OF CURRENT FLOW IN THE BUCK-BOOST COIL

The change in operating voltage of the magnetron is linear with the current flow through the coil. The power consumed varies as the square of the current. Ten watts of coil power allows a change of operating voltage by $\pm 22\%$. The same concept is being applied to the design concept of the full-scale SPS magnetron.

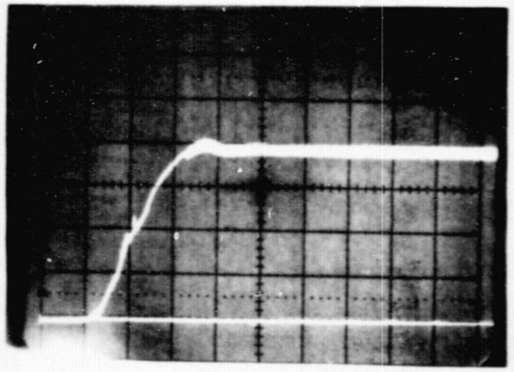


Magnetron Anode Voltage and Power Dissipated in Buck-boost Coil as Function of Current in Buck-boost Coil. The Relationship of Anode Voltage to Coil Current is Very Linear as Shown.

MAGNETRON STARTING PROCEDURE MADE POSSIBLE BY USE OF AMPLITUDE CONTROL CIRCUIT

The general objective in starting the tube is to prevent generation of power within the tube while the filament is being brought up to operating temperature. This is accomplished by placing a value of magnetic field on the tube which will prevent it from drawing current from the power supply even if the filament is hot. This is done through a temporary false output signal to the amplitude control servo. Then when the filament is sufficiently hot the amplitude control system is activated and the external filament power is turned off. The tube then goes into its normal mode of operation after a starting transient period of the order of three to four milliseconds.

Experimentally it has been found necessary to apply external power to the heater for five seconds to allow it to reach full temperature equilibrium.



OPERATING DATA

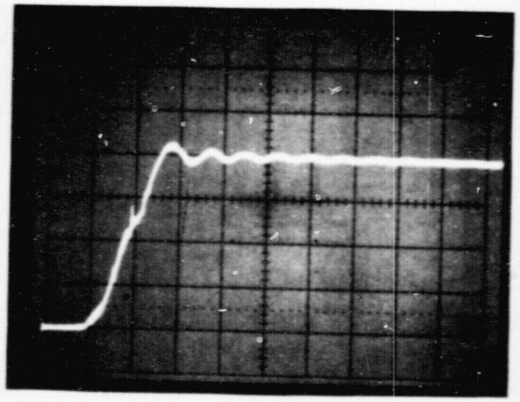
Tube #12 in directional amplifier circuit driven with 10 watts at 2453 MHz.

Filament E_f = 3.7 V, I_f = 13.5 A for 5 sec.

Operate conditions: E_b = 3900 volts, I_b = 300 mA, I_f = 0

Buck-boost coil saturated at 1.37 A initially.

Time scale of photo- 2 mV./div.

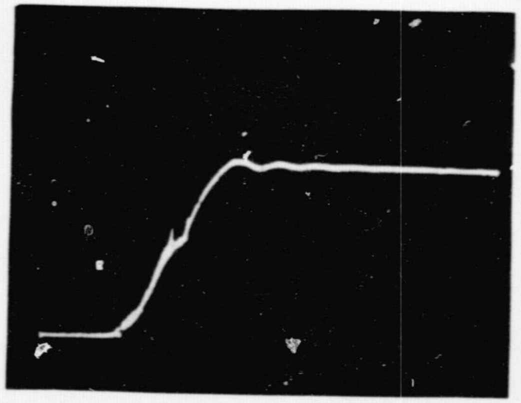


Tube #12 in directional amplifier circuit driven with 10 watts at 2453 MHz.

Filament E_f = 4.5 V, I_f = 15.5 A for 5 sec.

Operate conditions: E_b = 3900 volts I_b = 300 mA, I_f = 0

Buck-boost coil saturated at 1.37 A initially.



Tube #12 in directional amplifier circuit driven with 10 watts at 2453 MHz.

Filament E_f = 4.5 V, I_f = 15.5 A for 5 sec.

Operate conditions: E_b = 3650 volts, I_b = 330 mA, I_f = 0

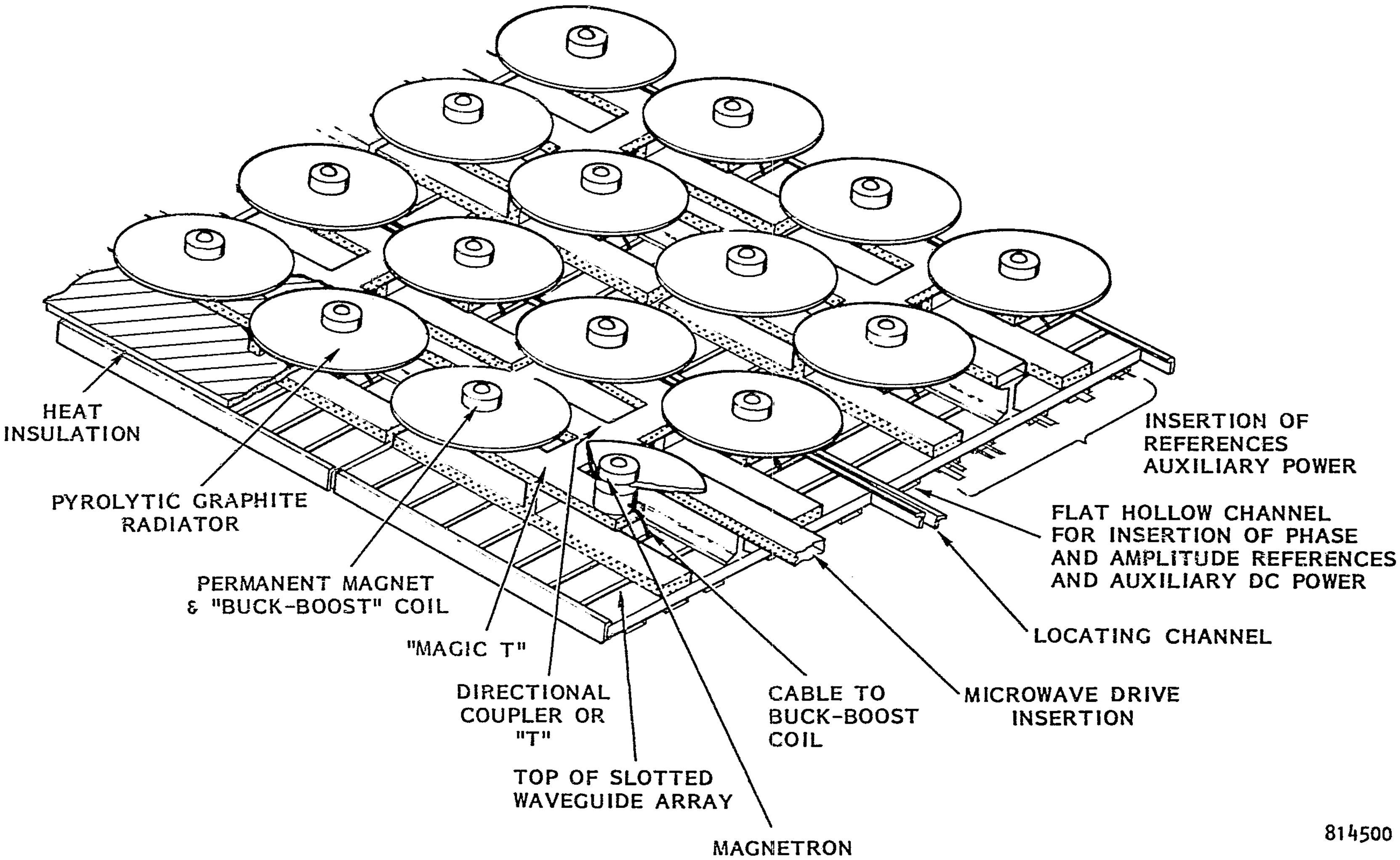
Buck-boost coil saturated at 1.37 A initially.

Transient Starting Behavior of Magnetron Directional Amplifier.

ASSEMBLY ARCHITECTURE FOR THE MAGNETRON DIRECTIONAL AMPLIFIER IN THE ANTENNA SUBARRAY

The diagram on the facing page shows two power modules. Power modules are two tubes wide and any number of tubes long, depending upon the dimensions of the subarray. Power modules are hard wired and individually tested and adjusted before installation. If the power module fails, or gets out of adjustment, the entire power module is taken out and replaced with another unit.

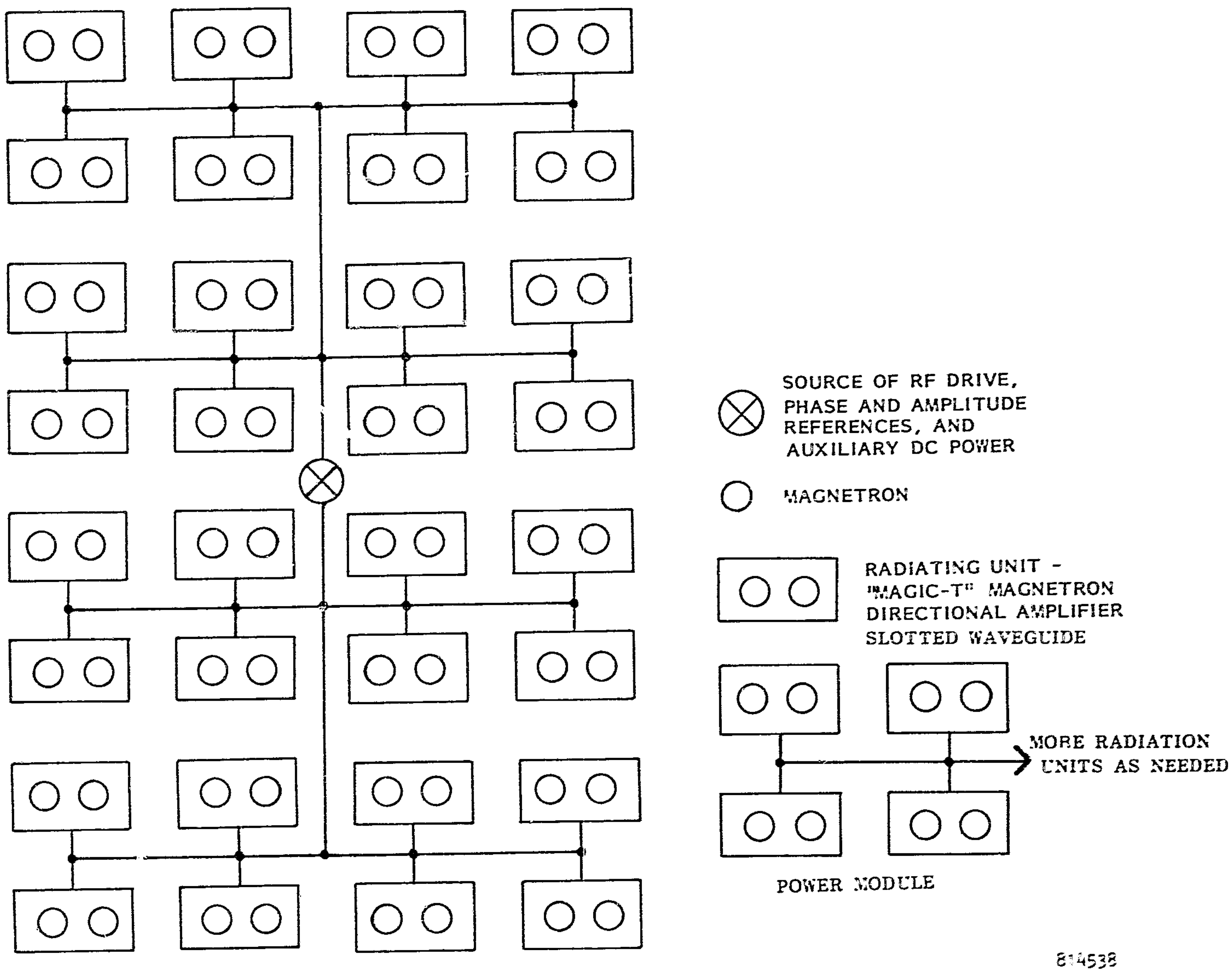
One of the objectives of this architecture is to place all the solid state devices on or near the slotted waveguide array which will be operating at a low temperature compatible with solid state devices. It seems to be appropriate to run any auxiliary electrical power and the control circuit references across the face of the waveguide in small conduits provided for that purpose.



Assembly Architecture for the Magnetron Directional Amplifier in the Antenna Subarray. Two Power Modules are Shown. Microwave Drive and all References and Auxiliary Power ar^ Inserted from the "Backbone" of the Subarray. The Array has Two Distinct Temperature Zones. The Top is Used to Radiate the Heat. The Bottom is Used for Mounting of Solid State Components.

COMPOSITION OF SUBARRAY SHOWING ARRANGEMENT OF POWER MODULES

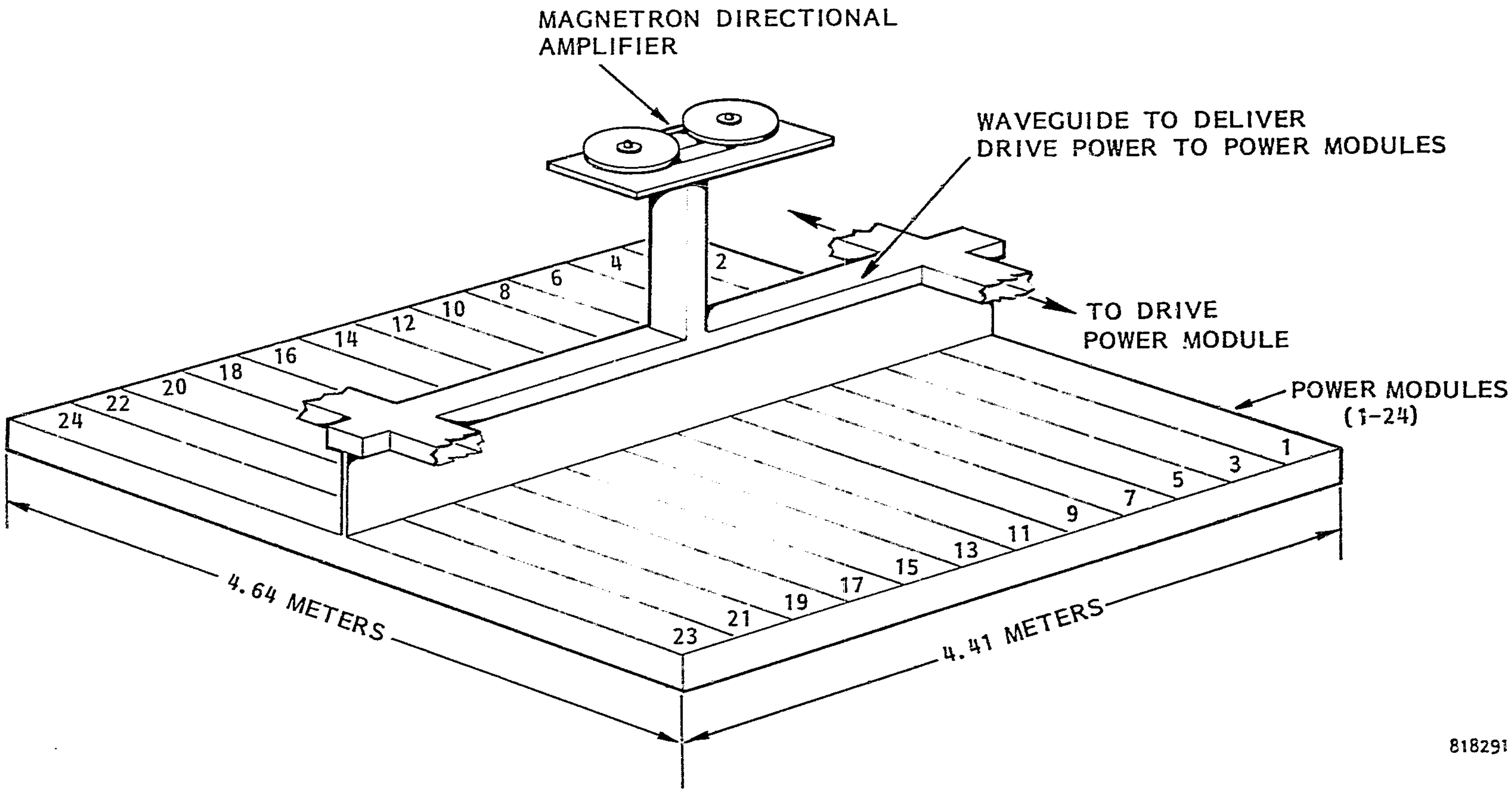
The schematic on the opposite page indicates the composition of the power modules and how the power modules in turn compose the subarray. Illustration on the next page indicates the location of the rf-drive source for the power modules.



Schematic of Subarray Made from Power Modules.

PHYSICAL ARRANGEMENT SHOWING LOCATION OF RF-DRIVE SOURCE FOR POWER MODULES IN THE SUBARRAY

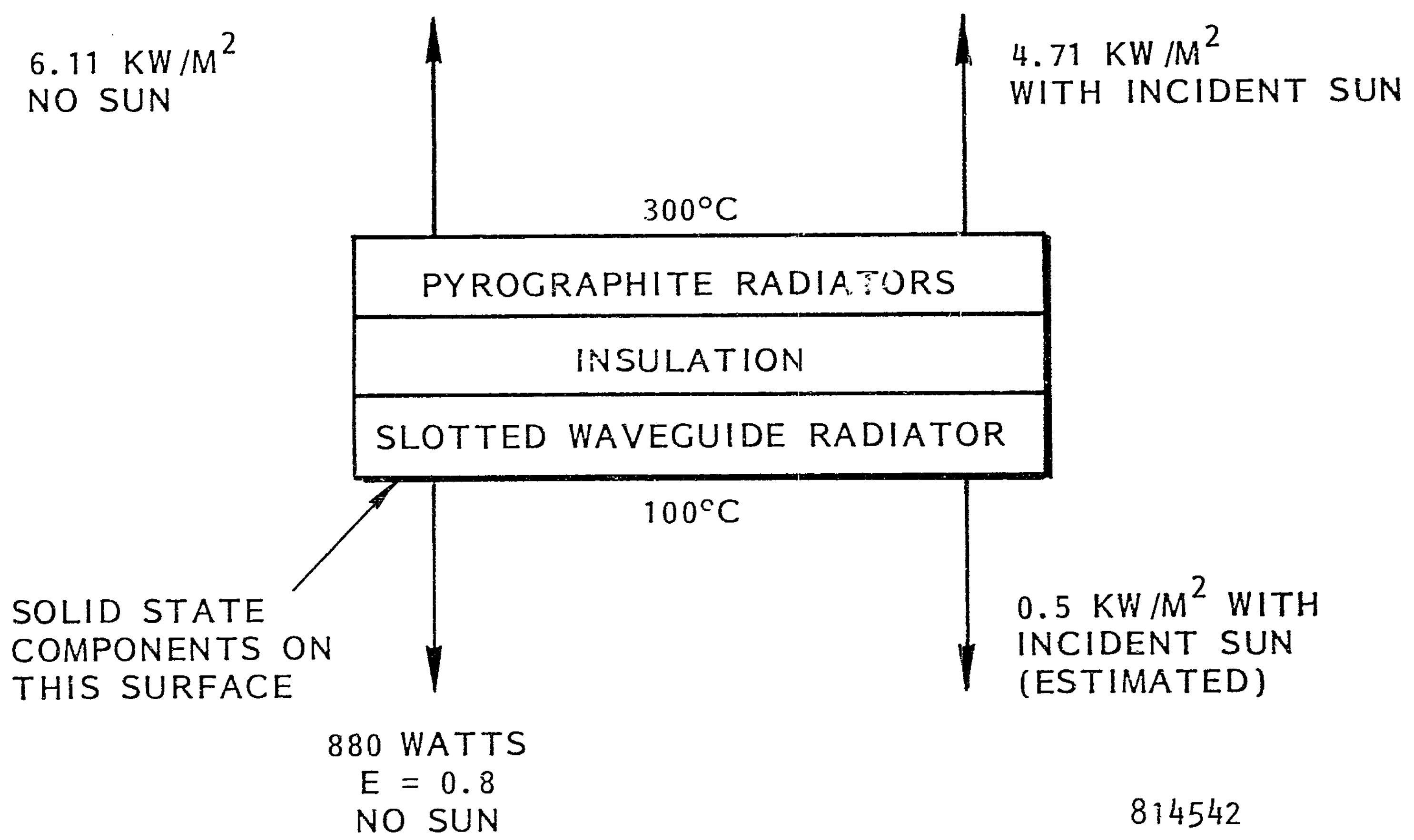
A single magnetron directional amplifier acts as a drive source in this design scenario for a subarray. The magnetron directional amplifier is mounted above the array so that it radiates heat into space on top side while radiation to it from bottom side is largely reflected back and distributed over a large area of the subarray. Phase and amplitude sensors and their location need special consideration.



Simplified Layout of Subarray Using Assumption that One Microwave Drive Source will Drive all of the Power Modules in the Array.

THERMAL INTERFACES IN POWER MODULE

The diagram on the facing page illustrates the partition of the power module into a top section which operates at high temperature to allow the dissipated power appearing in the form of heat to radiate into space and a bottom section which operates at a much lower temperature serves to radiate the microwave power and to house and protect the solid state components. An insulating blanket separates the two.

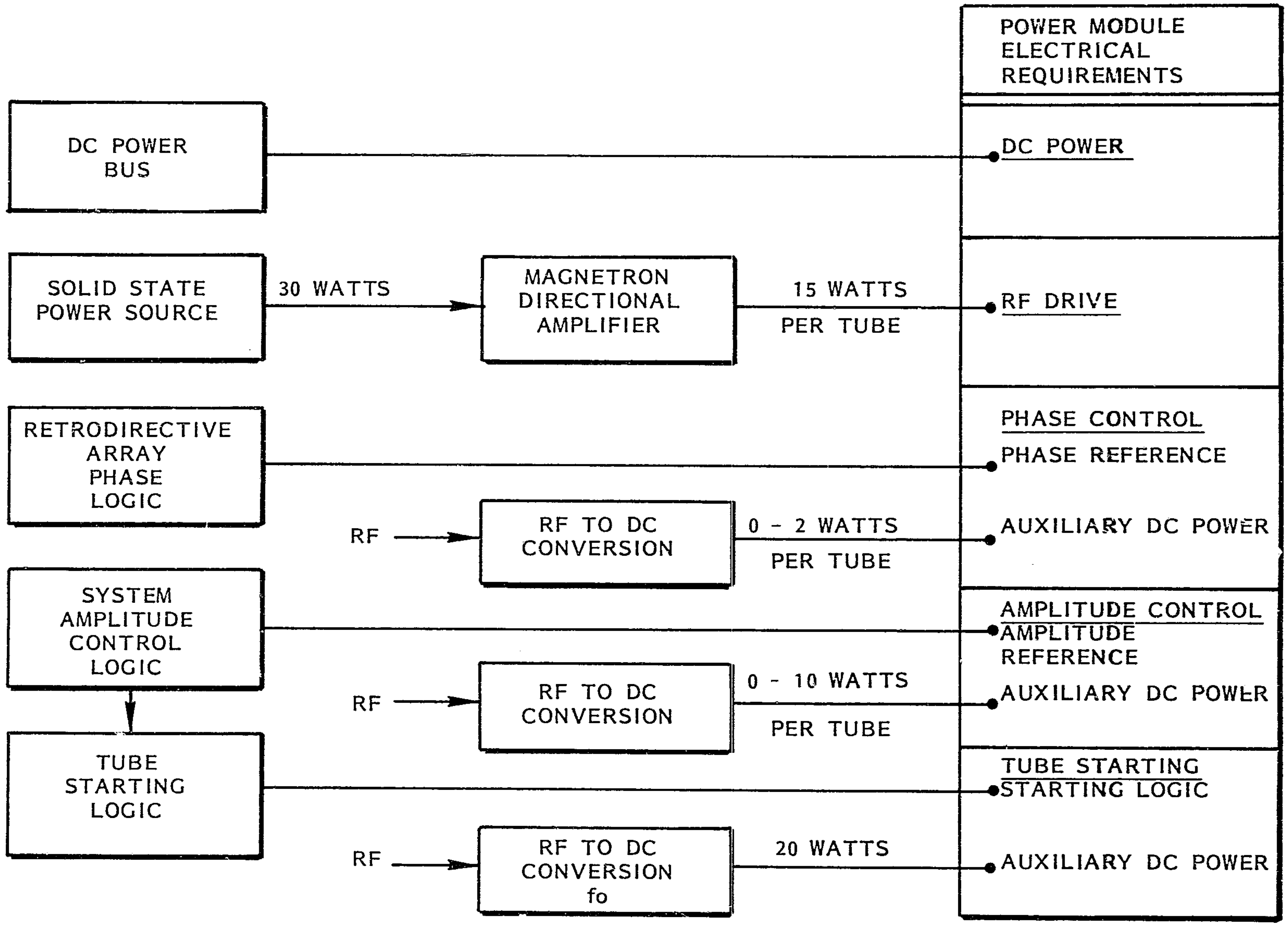


Thermal Interface in Power Module.

ELECTRICAL INPUT INTERFACE WITH POWER MODULE

The diagram on the facing page is believed to show all of the auxiliary power sources, and control references, that are needed when the power module is built around the magnetron directional amplifier. The concept of obtaining the auxiliary DC electrical power from microwave sources is also presented in the diagram, but much further investigation of the practicability of such a procedure is needed.

All of these interfaces have been checked out experimentally to some degree, including the tube starting procedure.



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Electrical Inputer Interface with Subarray Showing Use of RF to DC Conversion for Auxiliary DC Power Needed for the Power Modules.

AUXILIARY POWER REQUIREMENTS

The table on the opposite page indicates all of the auxiliary power that is required to operate a subarray. Most uses of auxiliary power require nearly ripple-free DC power. Needs of auxiliary power can be considered as either continuous or transient, the latter during start-up operations.

AUXILIARY POWER IN SUBARRAY**

Subarray Item Needing Auxiliary Power	Auxiliary Power Requirement	Continuous or Intermittent	Power Requirement Max.	Power Requirement Min.	AC or DC	Voltage Requirements	Potential Source of Prime Power**
Power Module	Amplitude Control	Continuous	10	0	DC	+20 −20	Bled from MDA* Driver to Start. Self Supplying After
	Phase Control	Continuous	2	0	DC	+20 −20	
	Magnetron Start	Starting 5 Sec.	70		DC or AC	5	Dedicated MDA*
MDA* RF Driver for Power Module	Amplitude Control	Continuous	10	0	DC	+20 −20	Battery to Start
	Phase Control	Continuous	2	0	DC	+20 −20	Self Supplying After
	Magnetron Start	Starting 5 Sec.	70		DC or AC	5	Battery
Solid State RF Driver	Power to Operate	Continuous	30	30	DC	+30	Battery to Start Bled from MDA* Driver
Dedicated MDA* for Auxiliary Power	Amplitude Control	Continuous	10	0	DC	+20 −20	Battery to Start
	Phase Control	Continuous	2	0	DC	+20 −20	Self Supplying After
	Magnetron Start	Starting 5 Sec.	70	0	DC or AC	5	Battery
Phase Control Center	Power to Operate	Continuous	100	100	DC	+30	Battery to Start Bled from MDA After

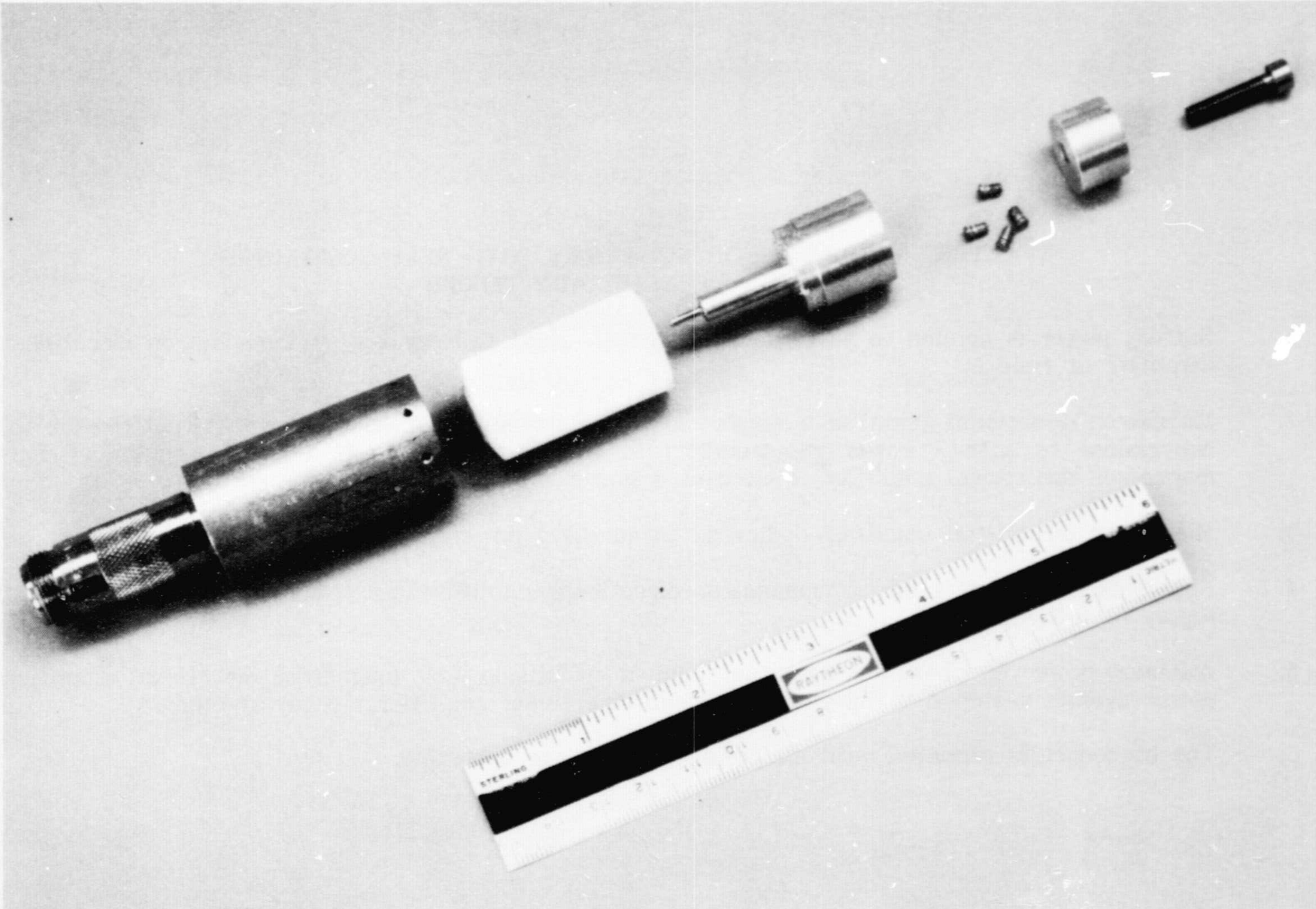
*MDA Means Magnetron Directional Amplifier

RECTIFICATION OF MICROWAVE POWER TO DC POWER AS AUXILIARY POWER SOURCE

Electrical power in the SPS is characterized as being either high voltage (20 kV) DC or microwave in nature. Conversion of 20 kilovolt DC to low DC voltage levels is a difficult procedure in the SPS if traditional methods are used. The ready availability of large amounts of efficiently generated microwave power in combination with an efficient microwave to DC rectification process that has been demonstrated in the rectenna can provide an alternate route and perhaps a preferable one to meet the needs for low-voltage auxiliary power.

In the examination of the requirements discussed on the previous page it is of interest that a single rectenna element supply packaged in a different manner and mounted on the face of the transmitting antenna for cooling purposes could supply the power necessary for the phase and amplitude tracking circuits in the "radiating unit" consisting of magnetron directional amplifier and antenna.

For the application involving the transient heating of the magnetron filaments for starting purposes large amounts of current will be required and approaches such as the one shown on the opposite page will need to be investigated and developed.



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Exploded View of the Model of the Proposed Arrangement for Obtaining High Current at Low Voltage from a 50 ohm Source of Microwave Power.

STARTING SCENARIO FOR SUBARRAY WITH SELF-CONTAINED SOURCE OF AUXILIARY POWER

1. Battery power is applied to phase control center, solid state driver, and magnetron directional amplifier at time 0.

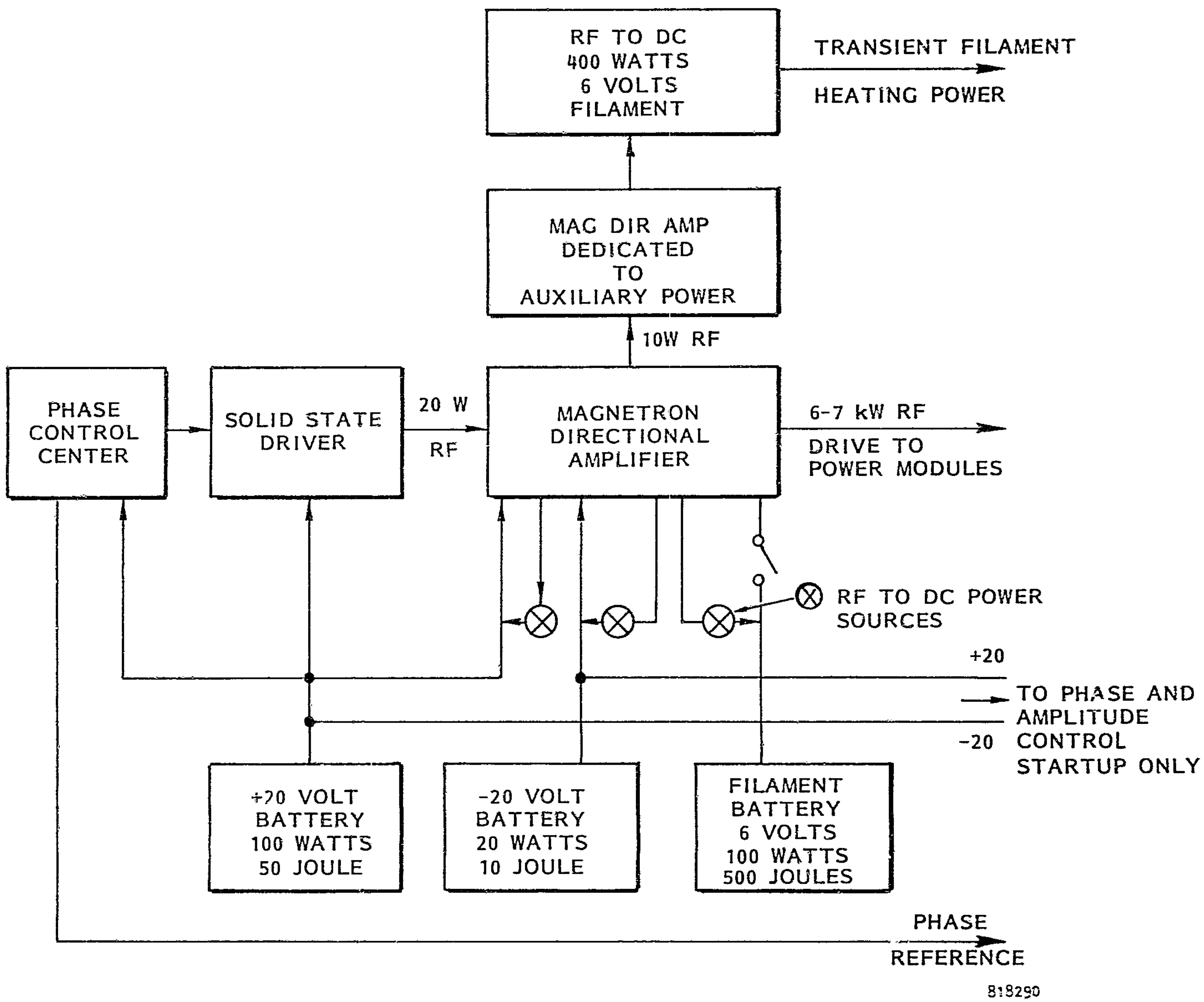
2. Magnetron directional amplifier is started in +5 seconds and supplies DC power (by microwave to DC conversion) to satisfy power requirements in phase and amplitude control circuits of inboard magnetron directional amplifier in each of 4 power modules.

3. Magnetron directional amplifier dedicated to auxiliary power is started in +10 seconds.

4. Filaments in each of 4 inboard magnetron directional amplifiers are heated from dedicated auxiliary supply in +15 seconds.

5. Auxiliary power for phase and amplitude control circuits in next magnetron directional amplifiers in power module switched to inboard magnetron directional amplifier already started.

6. The procedure is repeated until all power modules are operating.



Schematic of Arrangement for Containing All Sources of Auxiliary Power within the Subarray.

DESIGN OF THE MAGNETRON-PACKAGE

The magnetron package on the opposite page is shown to consist of:

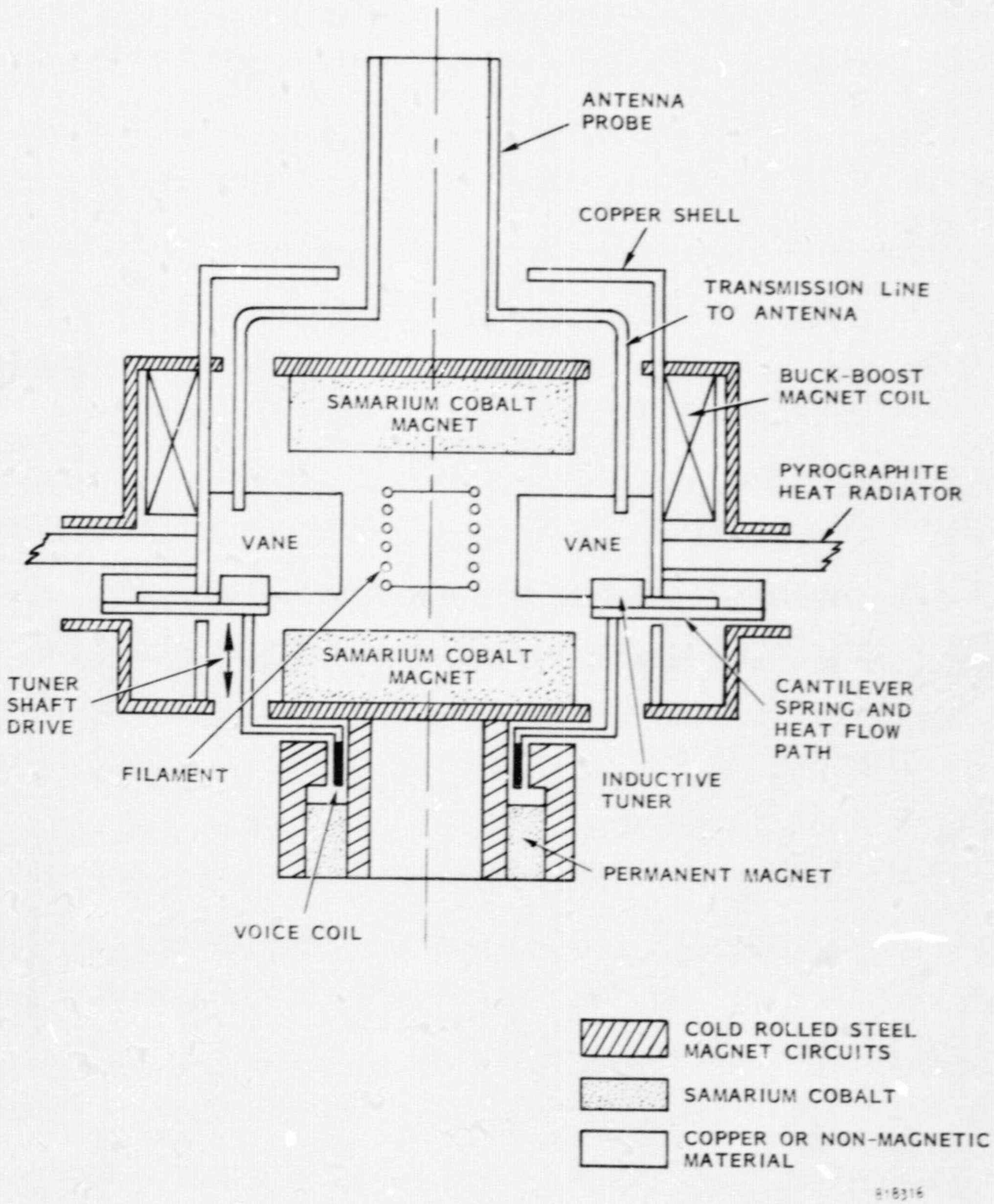
1. Basic tube essentials for conversion of DC to microwave power: magnetic field, filament, anode cylinder and microwave circuit.

2. Pyrographite radiator.

3. Buck-boost coils to assist with control of amplitude of output power.

4. Solenoid or "voice coil" actuated mechanical tuner for phase control purposes.

Total mass is estimated to be slightly over one kilogram and the tube generates power in the range of 3.2 to 5.0 kilowatts.



Cross Section of Magnetron Design Showing Permanent Magnets, Buck-Boost Coils for Amplitude Control and "Voice Coil" Driven Tuner for Phase Control. Details of Support Filament are not shown.

ESTIMATED MASS OF THE MAGNETRON PACKAGE

A breakdown of the estimated mass of the magnetron package is given on the opposite page.

ESTIMATED MASS OF PACKAGED MAGNETRON INCLUDING COOLING, AMPLITUDE CONTROL, PHASE CONTROL AND POWER CONDITIONING FUNCTION

Function	Item	Mass	% of Total	Accuracy Estimate of Final Weight	How Estimated	Total Mass of Function	% of Total	KG/KW		Power Output	
								85%	90%	85%	90%
Power Generation	Antenna Probe	11	1.0	±20	Computed	404	39.6	0.13	0.09	3.2	5.0
	Copper Vanes	44	4.3	± 5	Computed					3.2	5.0
	Copper Shell	45	4.4	±20	Computed					3.2	5.0
	Ceramics	30	2.9	±10	Measured					3.2	5.0
	Filament	8	0.8	±10	Measured					3.2	5.0
	Magnetic Circuit Including Sm Co Magnets	266	26.1	±10	Measured					3.2	5.0
Phase Control	Voice Coil & Inductive Tuner	64	6.2	±30	Computed	64	6.2	0.02	0.01	3.2	5.0
Amplitude Control Power Conditioning	Buck-Boost Coil	200	19.6	-50 +100	Roughly	200	19.6	0.06	0.04	3.2	5.0
Cooling	Pyrographite Radiator	350	34.3	±10	Computed	350	34.3	0.11	0.07	3.2	5.0
All Functions		1018	100%			1018	100%	0.32	0.20	3.2	5.0

THE PYROGRAPHITE RADIATOR DESIGN

"Pyrographite", or pyrolytic graphite is a key material in making it possible to passively radiate the dissipated power in the magnetron without an excessive mass penalty. Pyrographite has at least twice the heat conductivity of copper in the temperature region of interest and it has a density which is only one-quarter that of copper. Further it has a natural emissivity of 0.92, and a vapor pressure that is negligible.

The size of the pyrographite radiator is determined by the architecture, or more specifically by the size of the slotted waveguide radiator that is associated with the magnetron that feeds it. The slotted waveguide radiator effectively quantizes the graphite radiator in diameter steps of 18.4 cm, 36.8 cm, 55.2 cm, etc. and it also quantizes the power rating of the magnetron. The 18.4 cm dimension represents too small a magnetron, while the 55.2 cm diameter represents a radiator mass that would be considered excessive as well as a marginally acceptable tube on the high power side.

Because the diameter of the radiator is determined to be 36.8 cm, the design investigation is considerably simplified.

The photograph on the opposite page is of a mechanical mockup of a magnetron anode surrounded with a "pyrographite" radiator simulated by a radiator fashioned from aluminum material and painted black. The magnetron anode used in the photograph is not of the intended SPS design.

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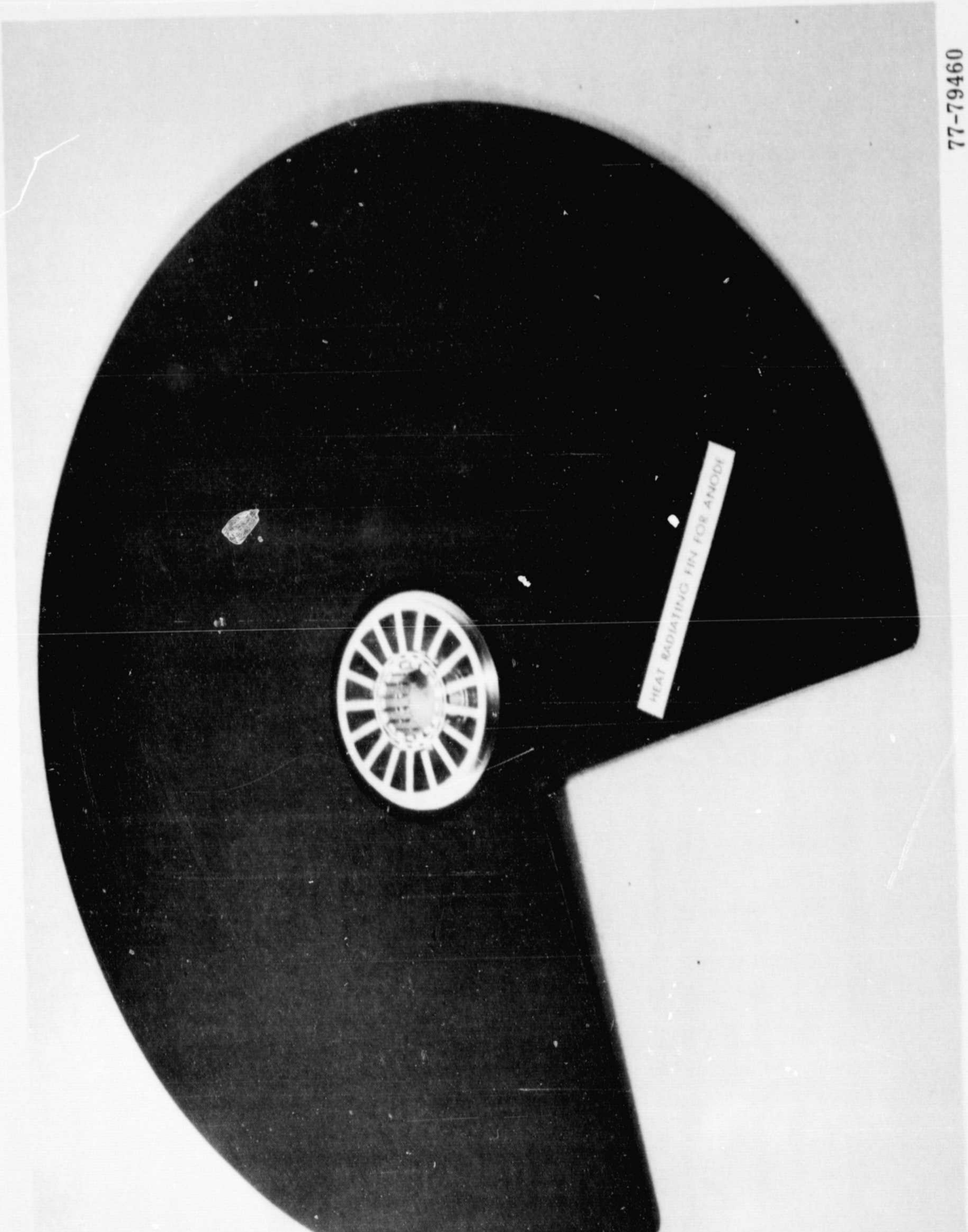


Magnetron with Pyrographite Radiator.

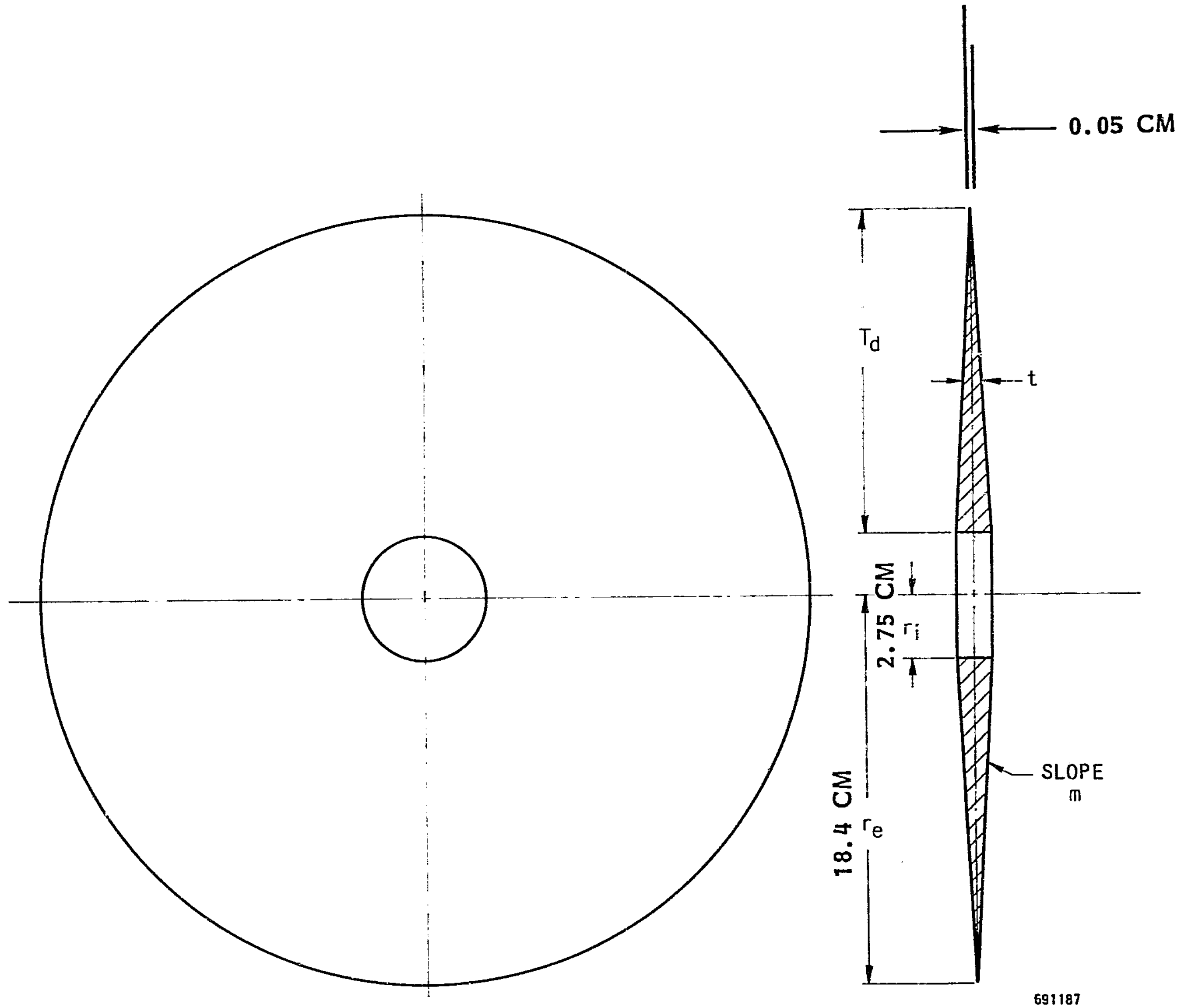
ORIGINAL PAGE IS
OF POOR QUALITY

THE PYROGRAPHITE RADIATOR DESIGN

The outside diameter of the fin is fixed by the slotted waveguide dimensions and the inside diameter by the outside diameter of the tube anode. The fin is assumed to have a flat taper, from the inside radius to the outer radius where the thickness of the fin is left at 0.05 cm, as a practical consideration.

The design investigation problem is to assume a temperature at the tip of the radiator and then work back towards the center through a series of concentric rings, taking into consideration the power radiated into space from each ring, and the temperature drop that occurs in each ring by the heat passing through it to outer concentric rings. Eventually, the inner radius is arrived at, together with the temperature of the radiating fin at that point and the amount of heat flux or power that is flowing outward. The variables in this investigation are the thickness at the root (inner radius) of the radiating fin, and the temperature of the fin at its outer radius. The results of this investigation are given on the next page. A computer program was used to generate the large amount of data.

The mass of the radiator is easily determined from the thickness of the radiator at its root and the arbitrarily selected 0.050 cm thickness at the fin tip. The mass of the radiator fin can be correlated with its ability to passively radiate heat.

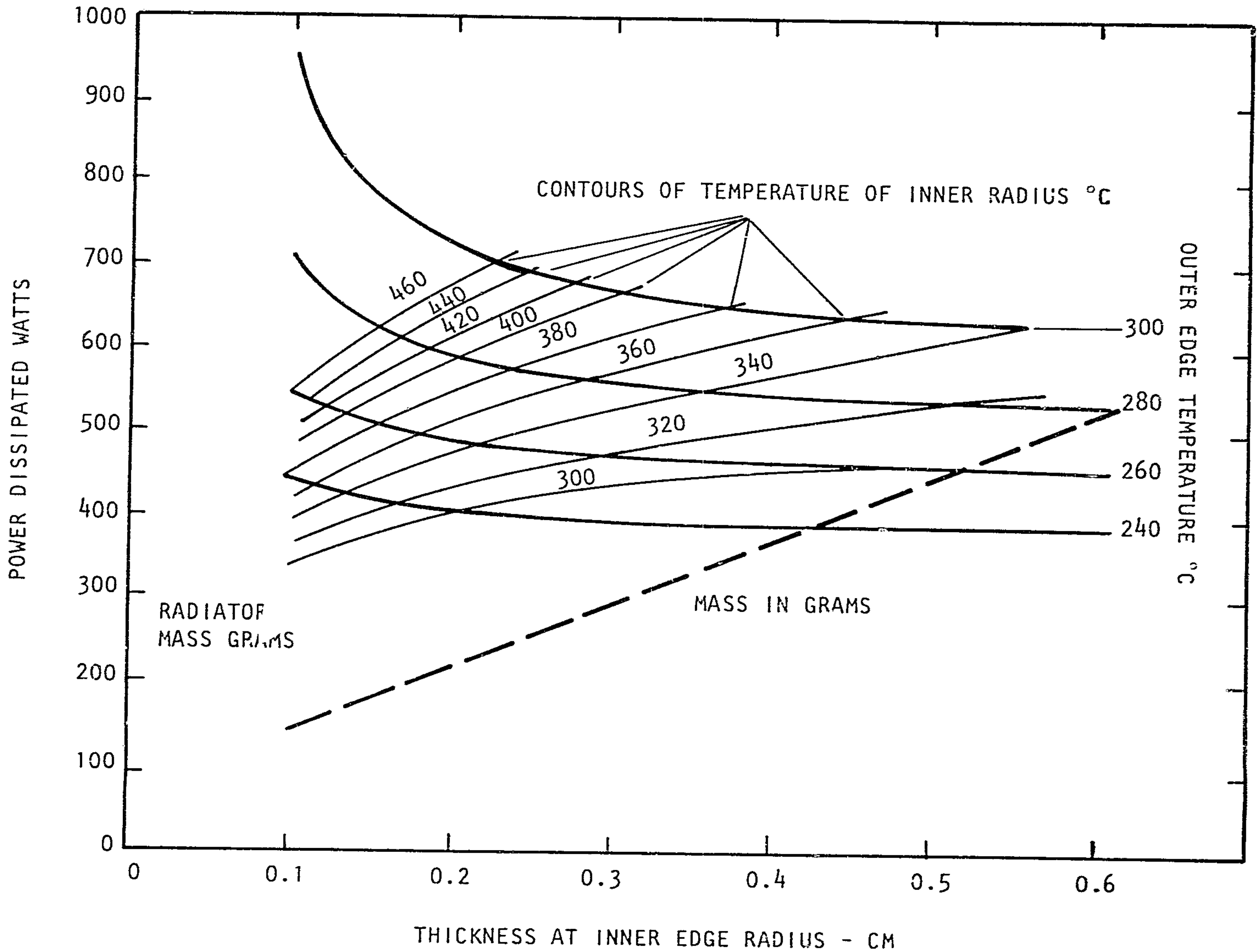


Drawing of the Shape of the Cooling Fin for the Microwave Generator. Heat Flows Radially from the Generator at Radius r_i, and is Radiated from the Top Surface. There Will Be a Temperature Drop T_d from r_e to r_i. Diameter of Radiator is Determined by Dimensions of the Slotted Waveguide Radiator.

CHART OF DATA FOR DESIGNING PYROGRAPHITE RADIATING FINS

The chart of computer generated data on the facing page provides data from which to select pyrographite radiator designs. The selection process is as follows: (1) determine the desired value of power to be dissipated and project a horizontal line from the corresponding ordinate value on the graph, (2) note the point at which this line intersects with the desired temperature at the inner radius of the radiator, (3) drop a horizontal line from this point of intersection to determine both the mass of the radiator and its thickness at its inner radius.

The design data arrived at by computer agrees remarkably well with the design data derived several years ago working with considerably cruder tools. Based on the previous approach a dissipation capability of 560 watts corresponded to a mass of 420 grams, whereas the new design data indicates 350 grams for the same 560 watts to be dissipated. The new data covers a wide range of data and will be very useful in further study and design efforts.



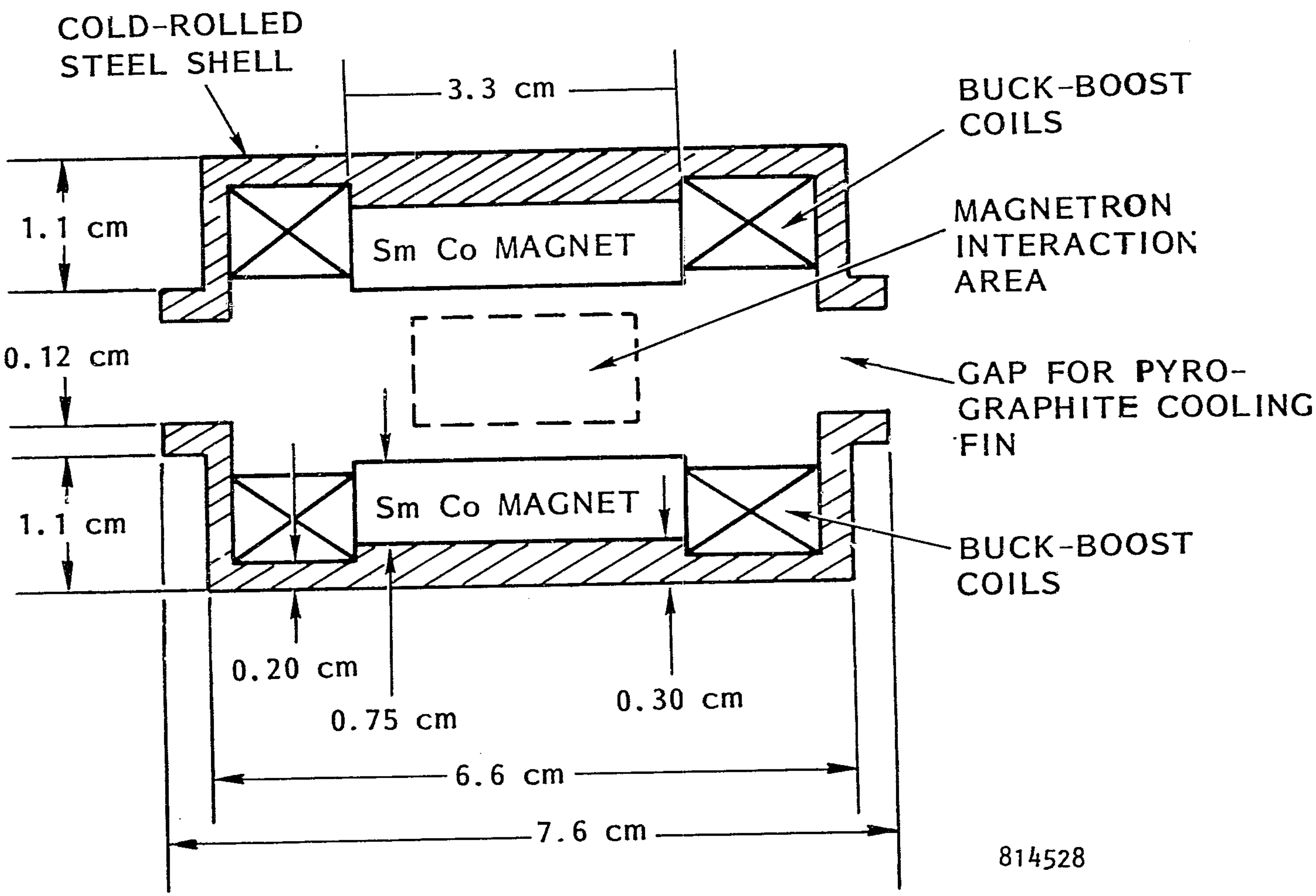
Graphic Data for Designing Pyrographite Radiators.

MAGNETIC CIRCUIT STUDY

The purpose of the magnetic circuit study was to narrow down the range of expected mass of the magnetic circuit for the SPS tube by analytical and experimental techniques. The design of the magnetic circuit was based upon the selection of the magnetron interaction area to consist of an anode 1 cm long, 2.0 cm in diameter, a cathode 1.25 cm in diameter, and a separation of pole pieces of 1.75 cm. The permanent magnets that were used experimentally were solid discs of samarium cobalt, 3.3 cm in diameter and 0.75 cm thick. The experimentally measured fields were 2575 gauss at the center, and 2240 gauss at the center of the cathode-anode interaction dimension. The computed values in assuming that the energy product of the samarium cobalt material was 14,000,000 were 2393 on the axis of the tube and 2070 at the center of the cathode-anode interaction area.

The value of 2070 is consistent with a value of 2700 to be obtained from samarium cobalt with an energy product of 24,000,000 which has been achieved in some laboratories. While this material is not yet available commercially orders are being accepted for material with an energy product of 22,000,000. A magnetic field of 2700 gauss is that value required in the SPS magnetron when it is operating at an anode voltage of 20 kilovolts.

The measured mass of the experimental circuit as shown in 266 grams, inclusive of the permanent magnet weight. The weight of the buck-boost coil was not included, but the estimated mass of a pair of coils is 200 grams.



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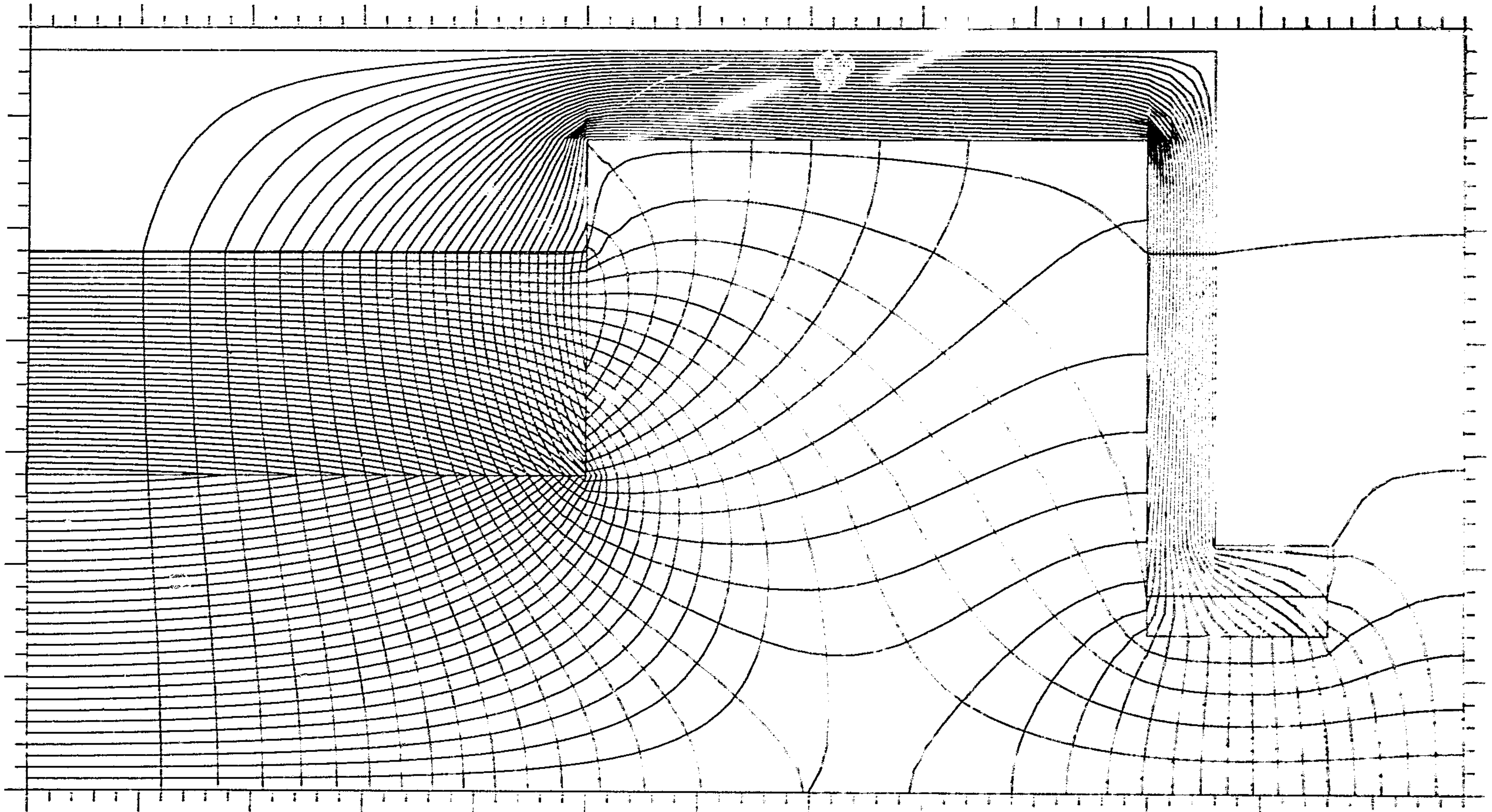
Magnetic Circuit Used for Computer Simulation and Experimental Measurement of Field in Interaction Area by Probe. The scale of the Illustration is 40% Oversize.

ANALYSIS OF MAGNETIC CIRCUIT BY COMPUTER PROGRAM

The figure on the opposite page is the result of an analysis carried out on the magnetic circuit on the previous page.



Computer Field Plots for Magnetic Circuit.

PROJECTED ELECTRICAL CHARACTERISTICS OF THE MAGNETRON PACKAGE

PROJECTED ELECTRICAL CHARACTERISTICS OF THE MAGNETRON PACKAGE

Item No.	Characteristics	Value	Determined By	Comments
1	Maximum Operating Anode Potential	20 kV	System Design Choice	
2	Minimum Anode Potential	15 kV	Limits of Amplitude Control	Depends Upon Magnetron Tuning for Phase Control
3	Operating Current	100 to 400 milliamperes	Dissipation Rating and Backheating of Cathode	Depends Upon Magnetron Tuning for Phase Control
4	Microwave Power Output at 85% Eff.	3.2 kW	0.56 kW Dissipation Rating and Efficiency	
5	Microwave Power Output at 90% Efficiency	5.0 kW	0.56 kW Dissipation and Efficiency	
6	Maximum Dissipation	0.56 kW	Radiator Dimensions 340°C Maximum Temp.	See Section 7.2 of this Report
7	Minimum Efficiency at 20 kV	85%	Present Design Capability	
8	Minimum Efficiency at 15 kV	82%	Reduced Because of Reduced B/B_o	See Section 7.4 of this Report
9	Maximum Efficiency at 20 kV	90%	Inherent Capability of Crossed Field Device	Much Development Needed
10	Maximum Efficiency at 15 kV	87%	Reduced Because of Reduced B/B_o	See Section 7.4 of this Report
11	Nominal Power Gain	20 dB		
12	Power Gain Range	0-30 dB	Selection of Phase Compensating Method	See Section 2.7 of this Report
13	Noise 30 MHz from Carrier	-120 DBC/* MGZ	Unresolved Determination of Noise Sources and Their Elimination	See Section 6.0 of this Report

*DBC - decibels relative to carrier power.

PROJECTED ELECTRICAL CHARACTERISTICS OF THE MAGNETRON PACKAGE

PROJECTED ELECTRICAL CHARACTERISTICS OF THE MAGNETRON PACKAGE (Continued)

Item No.	Characteristics	Value	Determined By	Comments
14	Added Phase Modulation Noise 50 KHz from Carrier	-114 DBC/	Measured	
15	Starting Filament Power	70 Watts	Filament Properties	See Section 3.0 of this Report
16	Operating Filament Power	0	Reduction of Noise	See Section 6.0 of this Report
17	Emission Life of Filament, 3.2 kW Output, 85% Eff.	>50 Years	3.2 kW Output, Anode Current Requirement	See Section 7.5 of this Report
18	Emission Life of Filament 5.0 kW Output, 90% Eff. Related to Life at 3.2 kW	0.8	Anode Current and Filament Temperature are Greater	See Section 7.5 of this Report
19	X-Ray Radiation	Negligible	Principle of Magnetron when Operating at Relatively Low Voltage	
20	Max. DC Power Consumed in Voice Coil	2 Watts	Tuner Design	See Section 7.6 of this Report
21	Max. DC Power Consumed by Buck-Boost Coil	20 Watts	Estimated	See Section 7.6 of this Report
22	Nominal Loaded Q of Magnetron	50	Needed High Circuit Efficiency	

PROJECTED MECHANICAL CHARACTERISTICS OF THE MAGNETRON PACKAGE

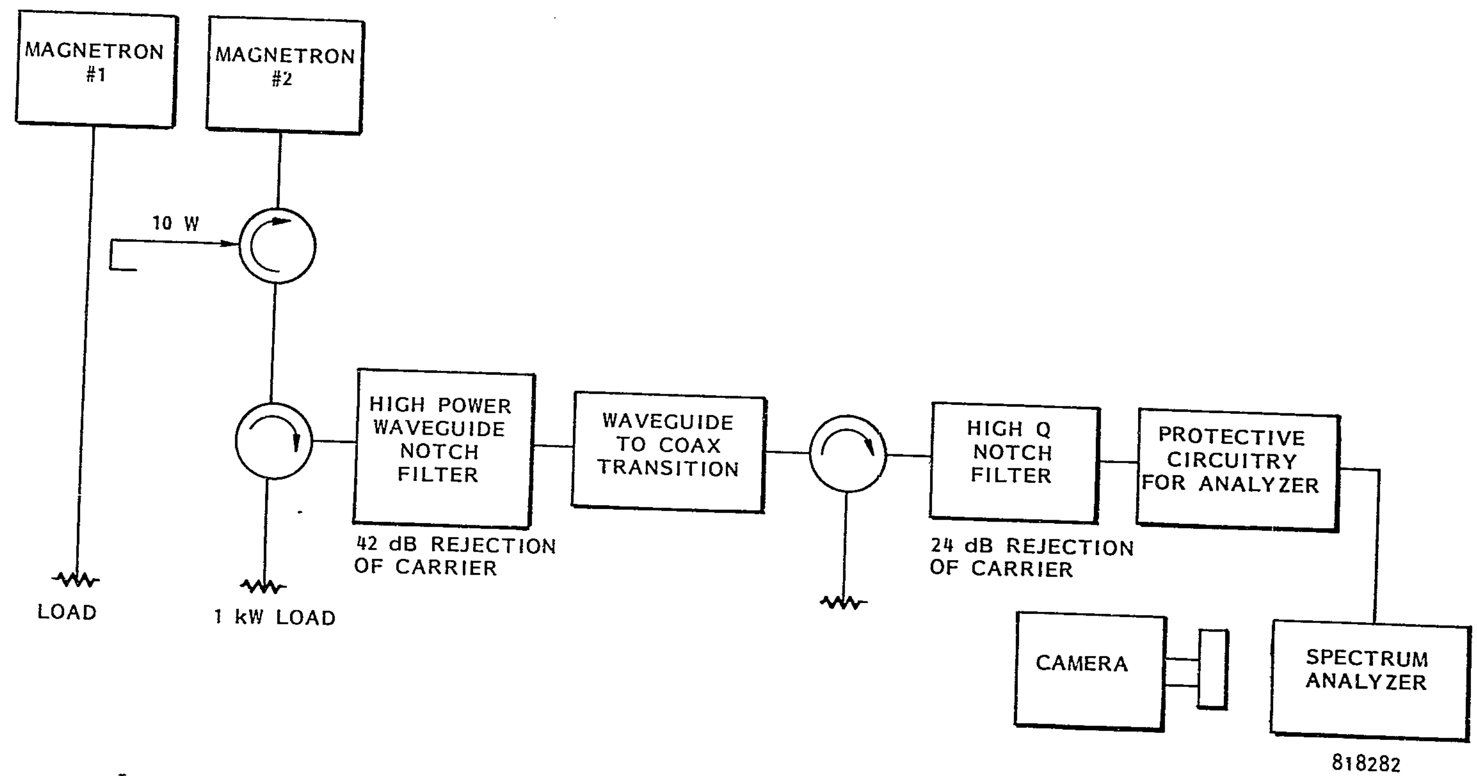
PROJECTED MECHANICAL CHARACTERISTICS OF THE MAGNETRON PACKAGE

Item No.	Characteristics	Value	Determined By	Comments
1	Mass	1.018 kG $\pm$0.2 kG	Design of Tube	See Section 7.6 of this Report
2	Radiator Diameter	36.8 CM	Design of Tube	See Section 7.2 of this Report
3	Axial Length	10 CM	Design of Tube	See Section 7.2 of this Report
4	Microwave Output	Antenna Probe	Design of Tube	
5	Maximum Operating Temperature of Pyrographite Radiator	$350^{o}C$		

INCREASED SENSITIVITY OF MEASUREMENTS OF BACKGROUND NOISE LEVEL

The determination of the background noise level of the microwave oven magnetron outside of the ISM band (2.40 - 2.50 GHz) would be very helpful in evaluating the radio frequency interference impact that tubes of the crossed-field principle might have. The measurements that had been made were limited by the residual noise level of the spectrum analyzer, even though a narrow band notch filter reduced the carrier level by a factor of 25 dB to prevent saturation and destruction of the analyzer by the carrier power. A task under this contract was to increase the measurement sensitivity by at least 20 dB by installing a high power notch filter for the carrier and in effect rejecting all but one part in 100,000 of the carrier signal so that all of the noise output of the microwave generator could feed directly into the spectrum analyzer.

This task has been successfully completed and the sensitivity of the measurements increased considerably beyond the 20 dB specified to a figure nearly 40 dB. The notch filter has a sharp characteristic with all but 2 dB of the 66 dB attenuation taking place within 10 MHz of the carrier.

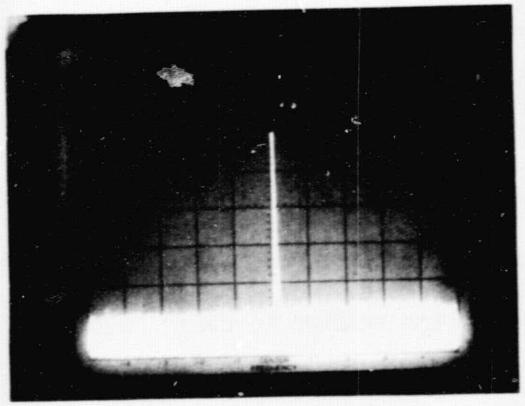


Improved Notched Filter Functional Test Block Diagram for Increased Sensitivity of Noise Measurements. Power not getting through high power waveguide filter is reflected back into a ferrite circulator and absorbed. Total filter consists of a cascade combination of a "T" section of WR 430 waveguide with a short in one arm adjusted to give minimum power transmission and a resonate cavity made from WR 284 tightly coupled to 3/4 inch coaxial line. A ferrite circulator is interposed between them to prevent coupling.

EXAMPLE OF LABORATORY SIGNAL TO NOISE RATIO MEASUREMENT

The photographs on the facing page are of the presentation on the Hewlett Packard spectrum analyzer when the test arrangement on the previous page was used. The total frequency covered by the photograph is 100 MHz, or the width of the ISM band. The residual noise level is that of the spectrum analyzer as shown in the middle photograph. The top photograph shows the spectrum with just the rf driver turned on. The bottom photograph shows the spectrum after the magnetron directional amplifier has been turned on. As the caption on the bottom photograph indicates the rms noise level in 1 Hz was 196 dB below the carrier.

The very low noise level was achieved by operating the tube with no external source to heat the filament and an external tuner on the cathode support assembly to further reduce the noise. There were no filters of any kind applied to the output of the magnetron to reduce the noise.



6-7 (a) Appearance of Drive Signal with 66 dB of Carrier Suppression Inserted.

Total Frequency Scan = 100 MHz

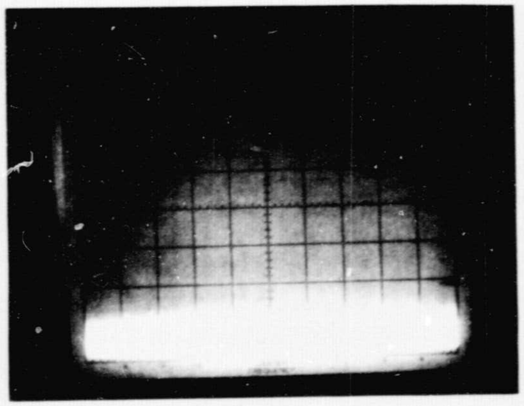
Vertical Scale = 10 dB/div.

Frequency - 2450 MHz

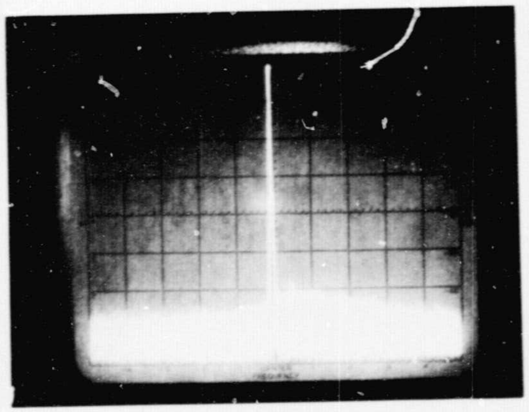
Noise at Bottom of Scope is Noise in Analyzer.

10 MHz/Div. IFBW 300 KHz

Log Ref 100 dB + 8.0 dB



6-7 (b) Same Conditions Imposed on Analyzer as in 7(a) but with Drive Signal Source Removed.



6-7 (c) Presentation on Analyzer with Magnetron Directional Amplifier Using QKH2000 #13 Magnetron and Optimum Position of Short in Cathode Microwave Circuit.

Receiver Bandwidth = 300 KHz

Total Frequency Scan = 100 MHz

Vertical Scale = 10 dB/div.

Carrier Suppression = 66 dB

Signal to Peak Noise = 133 dB/300 KHz

Signal to RMS Noise = 142 dB/300 KHz

Spectral Noise Density - -196.8 dBc

Signal to Noise Ratio Measurements of Improved Sensitivity. Spectral Noise Density of 196 dB Below carrier was Measured.

RANDOM NOISE EMISSIONS FROM SPS TRANSMITTER RELATIVE TO CCIR REQUIREMENTS

The internationally adopted CCIR requirements, when applied to the SPS, would require that signals emitted from the SPS be no greater than -154 dBw/Meter^2/4 KHz. The table on the opposite page shows how the observed performance noted on the previous page relates to these requirements at the ISM band edges.

The measured noise level of 196 dB/Hz below a carrier level of 500 watts, corresponds to a noise level of only 0.77 microwatts being radiated for each 4 KHz of bandwidth from an SPS transmitter that is radiating a total carrier power of 7.7 gigawatts. If the noise level is radiated uniformly over a hemisphere, the density level at the Earth's surface will be 0.93×10^{-22} W/M^2 or 66.3 dB better than the CCIR requirement.

Of course, there will be some concentration of the noise because of the gain of the slotted waveguide array. It is expected that the random noise of the microwave oven magnetron will be coherent over the slotted waveguide radiator dimensions associated with the magnetron. In the most dense part of the array where most of the power is radiated that dimension is 0.3 square meters. The gain associated with this is 26 dB, bringing the noise level at the Earth's surface down to 32 dB better than the CCIR requirement. However, the bandwidth of the slotted waveguide radiator is not very good outside of the ISM band and it begins to deteriorate before reaching the band edges. Hence, the true level of the noise radiation based upon the measurements just discussed is expected to be somewhere between 58 dB and 32 dB better than the CCIR requirement. Of course, the sensitivity of these measurements is limited by the measurement technique and it is quite likely that the real noise level continues to drop precipitously outside the edges of the ISM band.

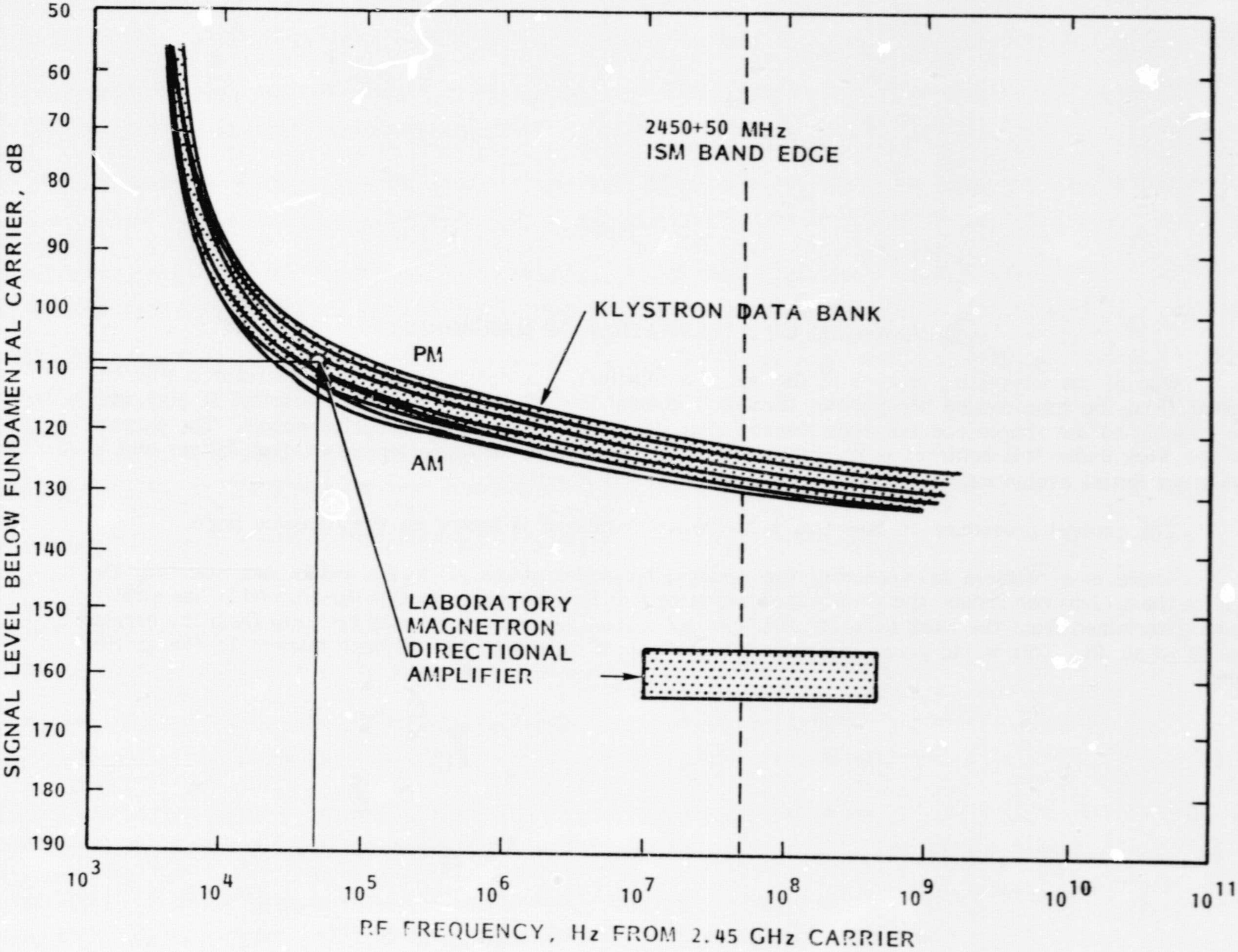
A comparison with the Klystron Data Bank that is explained more fully on the next page is also given.

RADIATED NOISE AND CCIR REQUIREMENTS
BASED ON RADIATED POWER
AT ISM BAND (2.4 - 2.5 GHz) EDGES

SUBJECT	KLYSTRON DATA BANK	LABORATORY MAGNETRON DIRECTIONAL AMPLIFIER
TOTAL NOISE RADIATED POWER IN 4 KHz BANDWIDTH FROM 7.7 GIGAWATT TRANSMITTER	0.00239 WATTS	0.00000075 WATTS
RADIATED POWER DENSITY PER SQUARE METER AT EARTH IN 4 KHz BAND ASSUMING UNIFORM RADIATION OVER A HEMISPHERE	0.29×10^{-18} W/M^2	0.93×10^{-22} W/M^2
SAFETY FACTOR OVER CCIR REQUIREMENTS (-154 DBW/M^2/4 KHz)	31.3 DB	66.3 DB
SAFETY FACTOR AFTER TAKING GAIN OF RADIATING APERTURES INTO ACCOUNT	-1.0 DB (4.06 SQ. METERS)	45.5 DB (0.29 SQ. METERS)

COMPARISON WITH KLYSTRON DATA BANK

One of the findings of JPL's investigation with the noise of generators for the SPS is that there appears to be no experimental data, documented or otherwide, of low noise emissions from klystrons that correspond to the low levels at which the laboratory magnetron directional amplifier has been operated. This is understandable in the context that noise removed from the carrier by 50 MHz is usually of little practical interest in the usual applications of microwaves to radar or communications, and even more understandable because of the difficulty of making the measurements and the special equipment which is required for them.



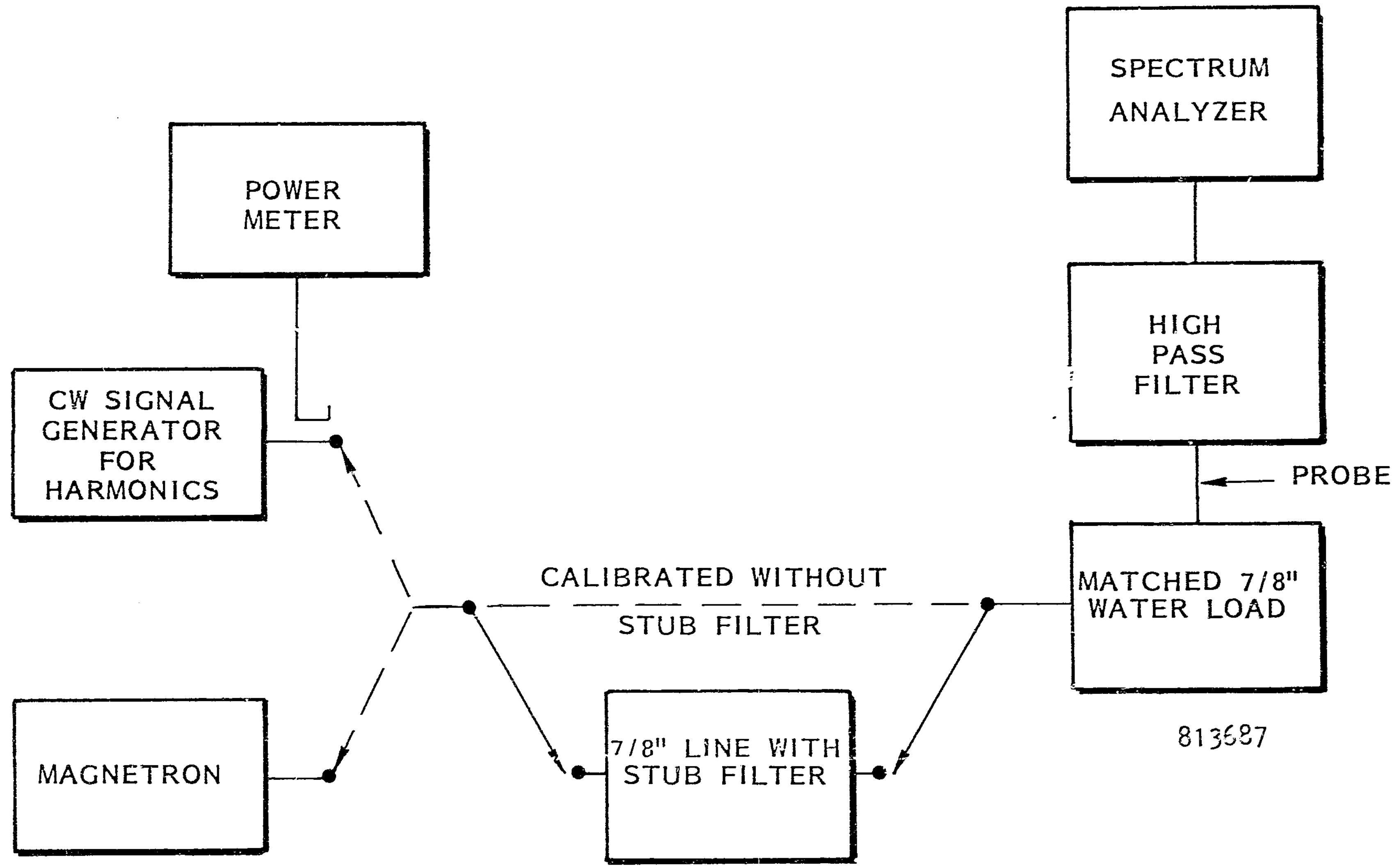
DC to RF Converter Spectral Noise Power Density in 4 kHz Bandwidth.

FEASIBILITY OF ATTENUATION OF HARMONICS

One of the interesting aspects of the use of a relatively low power microwave generator is that the power from the tube can be brought out through a coaxial line of relatively small diameter. It may then be possible to use simple coaxial stubs placed along the line to reflect the harmonic power. The purpose of the work under this contract is to obtain some initial data on the performance of such filters and to make an initial evaluation of whether such a procedure is practical.

The general procedure on how this is to be accomplished is shown on the opposite page.

There is a problem in measuring the residual harmonic power after the filters are inserted. The filters themselves can reduce the transmitted signal by a factor of approximately 40 dB, and it has already been determined from the work done for JPL that the initial harmonic level may be down from the carrier by 60 to 80 dB. This would place the harmonic level down by 100 to 120 dB with respect to the carrier level.

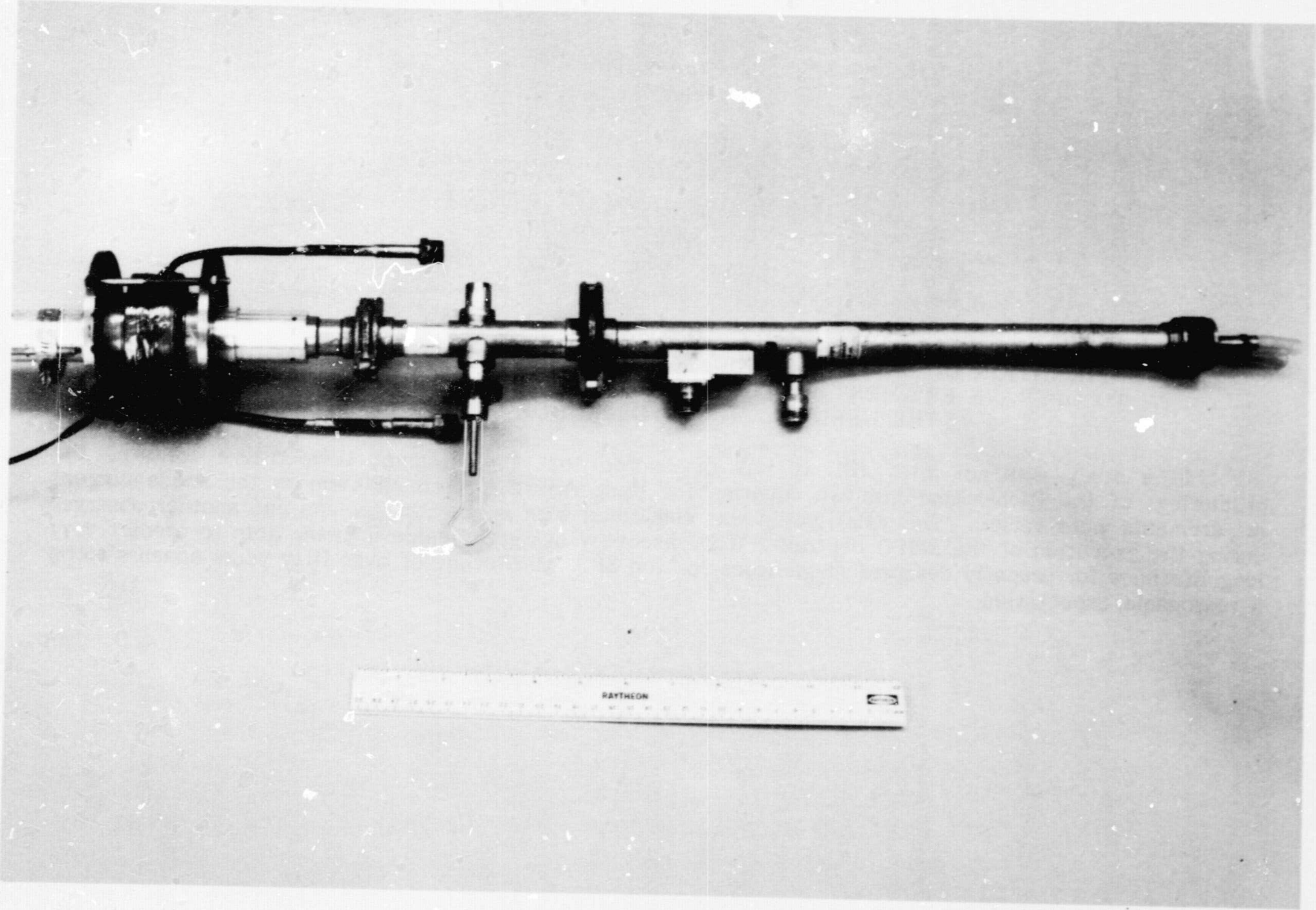


Arrangement for Investigating Stub-Type Filter for Reducing Harmonic Level.

REDUCTION OF HARMONIC LEVEL

Shown on the opposite page is the test arrangement in which the second harmonic output was reduced another 40 dB by the stub filter before the tube output reached the 50 ohm water load.

After the 40 dB additional attenuation the harmonic level was approximately 100 dB below the carrier.



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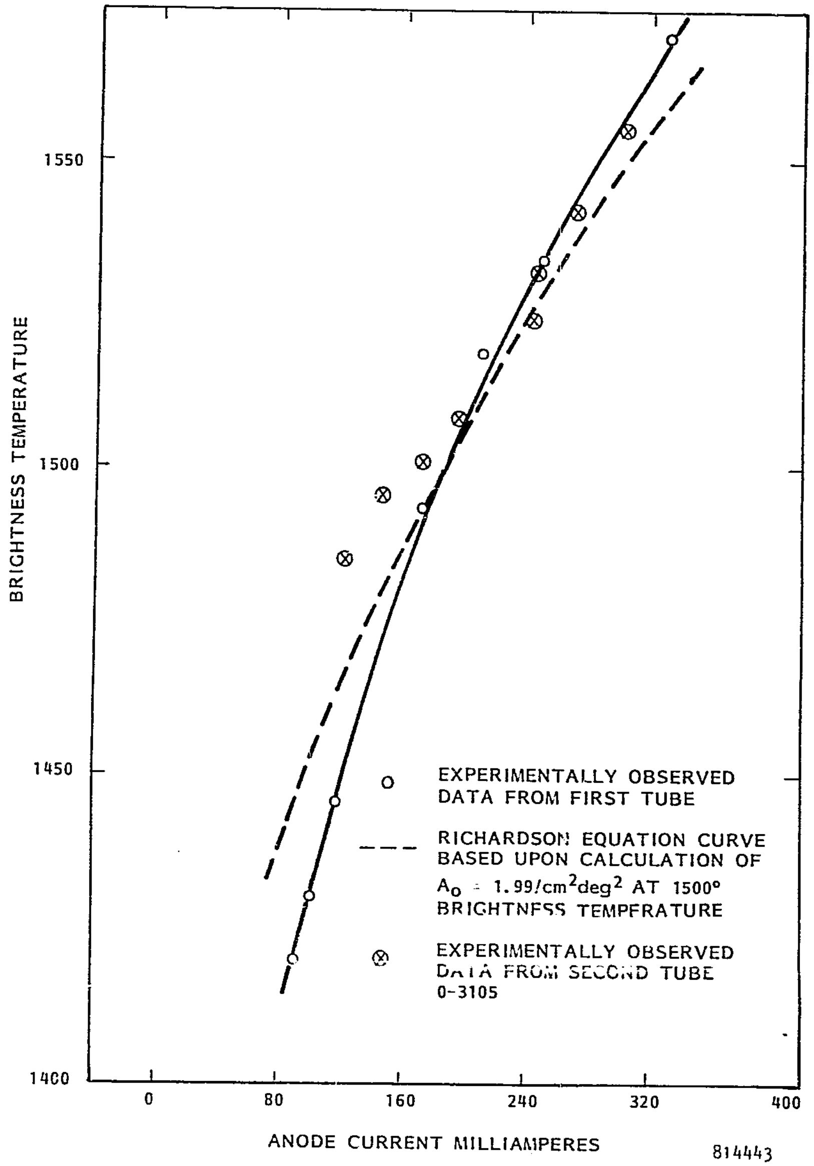
Experimental Arrangement for Measuring Additional Attenuation of Second Harmonic Power by Coaxial Stub in 7/8 Inch Coaxial Line Tuned to Reflect Second Harmonic Power.

CONFIRMATION OF SELF-CONTAINED REGULATING MECHANISM IN MAGNETRON TO OPERATE FILAMENT AT LOWEST POSSIBLE TEMPERATURE TO PROVIDE THE NEEDED AMOUNT OF ANODE CURRENT

In a study contract with JPL it was discovered that the filament temperature followed the predictions of the Richardson-Dushman equation for temperature limited emission as the anode current requirements were varied. This relationship was confirmed with another magnetron and another observer during the execution of the MSFC contract. This discovery has great value in being able to predict very long lifetimes for properly designed magnetrons for the SPS. A lifetime of over fifty years appears to be a reasonable expectation.



Experimentally Observed and Theoretically Predicted Relationship Between Cathode Temperature and Anode Current for Two Magnetrons with Optical Window.

THE PROPOSED DEVELOPMENT PROGRAM FOR THE MAGNETRON PACKAGE

The technology development program as shown on the opposite page is conceived as a four phase development program that starts with the use of the microwave oven magnetron as a desirable and economical intermediate vehicle, proceeds to a "terrestrial" version of the SPS magnetron, then to a "space" version that operates only in a good vacuum and at high temperature, and finally to a program of life test and small lot manufacture of the magnetron. Visualized as a two step effort Phase II and Phase III could be combined and the Phase III effort emphasized if the need to shorten the development time period for a space tube should occur.

PHASE I DEVELOPMENT

- Use of Microwave Oven Magnetron to Understand Sources of Low Level Noise and Inefficiency and Their Correction
- Invoives:

  IA - Measurement and Use of Existing Magnetrons

  IB - Design Changes and Tube Construction

USES

1. Understand Sources of Low Level Noise and Their Control
2. Find Sources of Inefficiency and Their Correction
3. Demonstration of Low Noise and High Efficiency

TIME 18 Months

COST A - $60,000

B - $150,000

PHASE II DEVELOPMENT

- Basic SPS Design Parameters
- Basic Format of Figure 7-1, but;
- Vacuum Envelope
- Water Cooled
- No Permanent Magnets
- Mechanically Tuned through Bellows

USES

1. Obtain Basic Operating Data
2. Identify Problem Areas and Reiterate Design to Remove Them.
3. Use in Ground Test Demonstration of Power Module and/or Subarray

TIME 24 Months

COST $800,000

Proposed Development of SPS Magnetron Package.

PROPOSED TECHNOLOGY DEVELOPMENT PROGRAM CONTINUED

PHASE III DEVELOPMENT

- Design & Test to All Space Requirements
- Samarium Cobalt Magnets
- No Vacuum Envelope
- Pyrographite Radiator
- Test in Vacuum Tank
- Operate at 350^{o}C

USES

1. Obtain All Data Needed for Space Except Life Test Data.
2. Impact of High Temperature Operation
3. Identify Problem Areas & Reiterate Design
4. Space Tests

24 Months

2,000,000*

PHASE IV DEVELOPMENT

- Manufacture of Significant Numer of Tubes
- Life Test Program

USES

1. Search for Long-Term Phenomena
2. Verify Adequacy of Design for Space Use

36 Months

2,000,000*

TOTAL

102 Months
8.5 Years

$4,910,000

*Does Not Include Test Facility.

Proposed Development of SPS Magnetron Package. (Continued)

ESTIMATED MAGNETRON PACKAGE PRODUCTION COSTS

Magnetron package production costs for large volume production have been estimated. These estimated costs use the current production costs of the microwave oven magnetron modified by the addition of the extra features of the pyrographite cooling fin, the buck-boost coil, the magnetron tuner with solenoid, and the samarium cobalt magnets.

The estimated cost of the portion of the SPS magnetron package that represents the basic generation of microwave power is actually less than the $25.00 price of the conventional microwave oven magnetron which includes a vacuum envelope, the processing of the tube, and relatively expensive packaging parts including the magnets. However, the extra features rapidly increase the cost of the tube. Even so, because of the increased power rating of the tube, the estimated costs per kilowatt of power generated are relatively low, ranging between $12.00 per kilowatt and $32.20 per kilowatt depending upon the range of cost estimated for the tube and its operating efficiency. The operating efficiency should be relatively independent of production costs, and depend cnly upon the cleverness of the engineer to achieve the potential efficiency of the crossed-field device.

These low costs are additionally significant in that the buck-boost coils provide a system power conditioning function and the "voice coil" tuner provides a phase tracking function that replaces a phase shifting device that would otherwise be needed in the power module.

BREAKDOWN OF COSTS FOR SPS MAGNETRON PACKAGE.

Elements of Cost	Cost Estimate in 1980 Dollars		Specific Cost $/kW			
			3.2 kW Tube 85%		5 kW Tube 90%	
	Low	High	Low Cost	High Cost	Low Cost	High Cost
Basic Tube	12	15	3.75	4.69	2.40	3.00
Pyrographite Fin	20	40	6.25	12.50	4.00	8.00
Buck-Boost Coil	3	8	0.94	2.50	0.60	1.60
Samarium Cobalt Magnets	20	30	6.25	9.38	4.00	6.00
Tuner Including Solenoid	5	10	1.56	3.13	1.00	2.00
Complete Package	60	103	18.75	32.20	12.00	20.60

ESTIMATE FOR THE MASS OF A 1 KILOMETER DIAMETER ARRAY IN A 5 GIGAWATT SYSTEM (AS DETERMINED AT THE INPUT OF THE UTILITY GRID)

With the support of the pyrographite, magnetic circuit, magnetron package studies and the architecture configuration studies under this contract and work done elsewhere on light weight slotted waveguide arrays, it is possible to estimate the total weight to the transmitting antenna except for the supporting structure, rotary joints, and main circuit breakers.

These estimates predict a total mass of 4.27×10^6 kilograms, which is considerably less than other recent studies have indicated.

Some understanding of how this mass was arrived at may be obtained from the table on the facing page.

Estimated Mass For Subarrays as Function of Tube Efficiency and Level of Total Power

Tube Efficiency	Radiator Diameter	Radiator Dissipation	Radiator Mass	Tube Mass	Total Mass	RF Output	Specific Mass (Satellite)	Mass for 7.5 GW	Mass for 11.8 GW	Waveguide & Remaining Microwave Mass	Heat Insulation Blanket	Total Mass of Subarrays*	Max Radiated Power Density	Power from Rectenna	Specific Mass Ground
%	cm	kw	kg	kg	kg	kW	kg/kW	kG x 10^6	kg x 10^6	kg x 10^6	kg x 10^6	kg x 10^6	kW/M^2	GW	kg/kW
85	36.8	0.56	0.42	0.55	0.97	3.17	0.31	2.3	--	1.47	0.5	4.27	23.4	5	0.85
90	30.0	0.35	0.17	0.55	0.72	3.17	0.23	1.7	--	1.47	0.5	3.67	23.4	5	0.73
90	36.8	0.56	0 42	0.55	0.97	5.04	0.19	--	2.3	1.47	0.5	4.27	37.2	7.9	0.54

* Does not include supporting structure, DC power bussing, rotary joints.

Assumptions:

Diameter of transmitting antenna is 1 kilometer.

67% efficiency from tube output to rectenna output assumed.

Mass of supporting structure, DC power bussing and main circuit breakers not included.

10 dB gaussian taper assumed for transmitter illumination.

SUMMARY AND CONCLUSIONS

Demonstration of the capability of the magnetron directional amplifier to track an amplitude and phase reference.

Start-up technique for magnetron making use of amplitude control was demonstrated.

A concept of tuning the magnetron to greatly expand the range of current and voltage over which the amplifier can track a reference. Concept has fast response, is free of mechanical sliding friction, and has a precedent in a magnetron designed for altimeter use.

Amplitude tracking capability of magnetron directional amplifier can be used in combination with logic and control center as the control element in a system that can respond rapidly to varying power needs at the electric utility interface, and/or can operate the system at maximum efficiency. It can eliminate need for conventional power conditioning as well.

Development of noise measuring procedure and equipment that measures spectral power density 195 dB below the carrier at frequencies removed from the carrier greater than 10 MHz.

Measurement of spectral power density of noise in laboratory magnetron directional amplifier that is 195 dB below the carrier.

Design for a magnetron package that includes the power generation function, the thermal cooling function, a buck-boost coil for amplitude control of the output, and a "voice coil" driven tuner for phase control. Projected design weighs slightly over a kilogram and develops between 3.2 and 5.0 kilowatts of microwave power depending upon the efficiency.

Development of a plan to obtain all auxiliary power requirements by converting microwave power to DC power by techniques already demonstrated in the rectenna.

Development of a start-up procedure utilizing three low power batteries so that each subarray is autonomous with exception of connection to 20 kilovolt power bus.

Investigations and refinements in the design of both the pyrographite radiator and magnetic circuits.

Preliminary data that stub filters can provide an additional 40 dB of attenuation of the second harmonic.

Magnetron package characteristics were projected.

Plan for magnetron-tube-package technology development drawn up. Time and cost were estimated.

RECOMMENDATIONS

Demonstrate that magnetron tuning controlled by the phase tracking feedback loop can remove the restriction placed on the operating range of anode voltage and current if high gain from the magnetron directional amplifier is required.

Determine the sources of low noise in the magnetron directional amplifier and remove them.

Determine the sources of inefficiency in the microwave oven magnetron and remove them.

Resolve which directional device should be combined with the magnetron to best meet the requirements imposed by use in space.

Check out the proposed architecture at the power module level which would incorporate phase and amplitude references, and involve an appropriate number of radiation units.